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Space-Time Processing for Tactical Mobile Ad Hoc Networks

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6. AUTHORS
James R. Zeidler, J.J. Garcia-Luna, Yingbo Hua, Hamid Jafarkhani, Tara Javidi, Michael Jensen, Srikanth Krisnamurthy, Laurence Milstein, John Proakis, Bhaskar Rao, A. Lee Swindlehurst, Michele Zorzi, Simon

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of California - San Diego
9500 Gilman Drive
MC 0934
La Jolla, CA 92093 -0934

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
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Research Triangle Park, NC 27709-2211

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13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
The use of electronically steerable antenna arrays, space-time multiple input multiple output (MIMO) signal processing techniques, and improved techniques for error correction have demonstrated the capability to greatly improve the performance of point-to-point communications for both commercial and tactical networks. In this project we have addressed the challenging question of how these technological developments can best be exploited in a tactical networking context, where signal interference and channel uncertainty issues have a tremendous impact

15. SUBJECT TERMS
ad hoc networks, wireless networks, MIMO, tactical networks, mobile networks, channel estimation, channel measurements

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		James Zeidler
					19b. TELEPHONE NUMBER: 858-534-5369

Report Title

Space-Time Processing for Tactical Mobile
Ad Hoc Networks

ABSTRACT

The use of electronically steerable antenna arrays, space-time multiple input multiple output (MIMO) signal processing techniques, and improved techniques for error correction have demonstrated the capability to greatly improve the performance of point-to-point communications for both commercial and tactical networks. In this project we have addressed the challenging question of how these technological developments can best be exploited in a tactical networking context, where signal interference and channel uncertainty issues have a tremendous impact on end-to-end system performance.

Tactical applications pose unique requirements for the network, including decentralized control to eliminate single points-of-failure, vulnerability to jamming and electronic warfare, and mission critical latency bounds for end-to-end data delivery. Moreover, a tactical network is generally composed of mobile nodes and the routing protocols must deal with a range of node mobilities and time varying channel conditions. This project has focused on the design of ad hoc networking architectures that utilize MIMO transmitters and receivers at each node of this mobile, decentralized tactical network. The goal of this program has been to define the best way to utilize multiple transmit and receive antennas at each node to improve the robustness, capacity, and quality of service of the network.

This report summarizes the significant advances that were achieved in this project concerning the underlying issues associated with incorporating the information available from the MIMO physical layer into the network routing and scheduling protocols for mobile ad hoc tactical networks.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Published Journals 2009-2010

Yingbo Hua

RONG, Y., TANG, X., and HUA, Y., “A unified framework for optimizing linear non-regenerative multicarrier MIMO relay communication systems,” IEEE Transactions on Signal Processing, Vol. 57, No. 12, pp. 4837-4852, Dec 2009.

RONG, Y., and HUA, Y., “Optimality of diagonalization of multi-hop MIMO relays,” IEEE Transactions on Wireless Communications, Vol. 8, No. 12, pp. 6068-6077, Dec. 2009.

DONG, X., RONG, Y., HUA, Y., “Cooperative power scheduling for a network of MIMO links,” IEEE Transactions on Wireless Communications, Vol. 9, No. 3, pp. 939-944, March 2010.

YU, Y., and HUA, Y., “Power allocation for a MIMO relay system with multiple-antenna users”, IEEE Transactions on Signal Processing, Vol. 58, No. 5, pp. 2823-2835, May 2010.

Hamid Jafarkhani

F. Li and H. Jafarkhani, "Multiple-Antenna Interference Cancellation and Detection for Two Users Using Precoders," IEEE Journal of Selected Topics in Signal Processing, Dec. 2009.

Siavash Ekbatani, Farzad Etemadi, and Hamid Jafarkhani; "Throughput Maximization Over Slowly Fading Channels Using Quantized and Erroneous Feedback"; IEEE Transactions on Communications, Vol. 57, No. 9, pp. 2528-2533, September, 2009

Michael Jensen

B. T. Quist and M. A. Jensen, “Optimal antenna radiation characteristics for diversity and MIMO systems,” IEEE Trans. Antennas Propag., vol. 57, no. 11, pp. 3474-3481, Nov. 2009.

J. W. Wallace and M. A. Jensen, “Sparse power angle spectrum estimation,” IEEE Trans. Antennas Propag., vol. 57, no. 8, pp. 2452-2460, Aug. 2009.

D. N. Evans and M. A. Jensen, “Near-optimal radiation patterns for antenna diversity,” IEEE Trans. Antennas Propag., to appear.
M. A. Jensen and B. K. Lau, “Uncoupled matching for active and passive impedances of coupled arrays in MIMO systems,” IEEE Trans. Antennas Propag., to appear.

Laurence Milstein

A. S. Ling and L. B. Milstein; "The Effects of Spatial Diversity and Imperfect Channel Estimation on Wideband MC-DS-CDMA and MC-CDMA"; IEEE Transactions on Communications, Vol. 57, No. 10, pp. 2988-3000, October, 2009

P. Amihood, E. Masry, L. B. Milstein, and J. G. Proakis; "The Effects of Channel Estimation Errors on a Nonlinear Precoder for Multiple Antenna Downlink Channels"; IEEE Transactions on Communications, Vol. 57, No. 11, pp. 3307-3315, November, 2009

John G. Proakis

P. Amihood, E. Masry, L.B. Milstein, J.G. Proakis, “The Effects of Channel Estimation Errors on a Nonlinear Precoder for Multiple Antenna Downlink Channels,” IEEE Transactions on Communications, vol. 57, no. 11, pp. 3307-3315, November 2009.

K. Stamatiou, J.G. Proakis and J.R. Zeidler, “Channel diversity in random wireless networks,” IEEE Transactions on Wireless Communications, Vol. 9, pp.2280-2289, July 2010.

Kostas Stamatiou, John G. Proakis and James R. Zeidler; "Spatial Multiplexing in Random Wireless Networks"; Advances in Electronics and Telecommunications, Vol. 1, No. 1, April, 2010

Bhaskar Rao

Y. Isukapalli and B. D. Rao, “Packet error probability of a transmit beamforming system with imperfect feedback,” IEEE Transactions on Signal Processing, Vol. 58, No. 4, Pages: 2298-2314, Apr. 2010.

Sagnik Ghosh, Bhaskar D. Rao, and James R. Zeidler; "Outage-Efficient Strategies for Multiuser MIMO Networks with Channel Distribution Information"; Accepted for publication in IEEE Transactions on Signal Processing, in press

Lee Swindlehurst

M. Nokleby and A. Swindlehurst, “Bargaining and MISO Interference Channel," EURASIP Journal of Applied Signal Processing, 2009.

Z. Han, A. Swindlehurst and K. J. R. Liu, “Optimization of MANET Connectivity via Smart Deployment/Movement of Unmanned Air Vehicles" IEEE Trans. on Vehicular Technology, September, 2009.

P. Zhan, K. Yu and A. Swindlehurst, “Wireless Relay Communications with Unmanned Aerial Vehicles: Performance and Optimization," submitted to IEEE Trans. on Aerospace & Electronic Systems, 2010 (to appear).

M. Larsen and A. Swindlehurst, “Power Allocation and Bit Loading for Spatial Multiplexing with Imperfect CSI," IEEE Trans. on Signal Processing, 2010 (to appear).

James Zeidler

Kostas Stamatiou, John G. Proakis and James R. Zeidler; "Spatial Multiplexing in Random Wireless Networks"; Advances in Electronics and Telecommunications, Vol. 1, No. 1, April, 2010

K. Stamatiou, J.G. Proakis and J. R. Zeidler, “Channel Diversity in Random Wireless Networks” IEEE Transactions on Wireless Communications, Vol. 9, pp 2280-2289,July, 2010.

Sagnik Ghosh, Bhaskar D. Rao, and James R. Zeidler; "Outage-Efficient Strategies for Multiuser MIMO Networks with Channel Distribution Information"; Accepted for publication in IEEE Transactions on Signal Processing, in press

Michele Zorzi

A. Munari, F. Rossetto, M. Zorzi, “Phoenix: Making Cooperation more Efficient through Network Coding in Wireless Networks”, IEEE Transactions on Wireless Communications, vol. 8, n. 10, pp. 5248-5258, Oct. 2009.

JJ Garcia-Luna

S. Karande, Z. Wang, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Optimal Unicast Capacity of Random Geometric Graphs: Impact of Multipacket Transmission and Reception, IEEE Journal on Selected Areas in Communications, Special Issue on Stochastic Geometry and Random Graphs for Wireless Networks, Vol. 27, No. 7, Sept. 2009.

Number of Papers published in peer-reviewed journals: 21

Number of Papers published in peer-reviewed journals: 21.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Published Conferences 2009-2010

Yingbo Hua

XU, S., and HUA, Y., “Source-relay optimization for a two-way MIMO relay system,” IEEE ICASSP, Dallas, TX, March 2010.

Hamid Jafarkhani

E. Koyuncu and H. Jafarkhani, ``Beamforming in Wireless Relay-Interference Networks with Quantized Feedback," IEEE Global Communications Conference (Globecom-09), Nov. 2009.

Tara Javidi

A. Bhorkar, M. Naghshvar, T. Javidi, B. Rao, “An Adaptive Opportunistic Routing Scheme for Wireless Ad-hoc Networks,” in Proceedings of IEEE International Symposium on Information Theory, 2009

M. Naghshvar, H. Zhuang, and T. Javidi, “A General Class of Throughput Optimal Routing Policies in Multi-hop Wireless Networks”, Allerton Conference, 2009.

Naghshvar, and T. Javidi, “Opportunistic Routing with Congestion Diversity in Wireless Multi-hop Networks,” in IEEE Infocom 2010.

K. Stamatiou, F. Rossetto, M. Haenggi, T. Javidi, J. Zeidler and M. Zorzi ``A delay-minimizing routing strategy for wireless multi-hop networks," in Proc. IEEEWorkshop on Spatial Stochastic Models for Wireless Networks (SPASWIN), Seoul, June 2009

Michael Jensen

Y. Shi, Y. Yang, and M. A. Jensen, “Channel covariance modeling for multi-user MIMO systems”, Proceedings of 2010 European Conference on Antennas and Propagation (EuCAP), Barcelona, Spain, Apr. 12-16, 2010. Invited

M. A. Jensen and B. K. Lau, “Uncoupled impedance matching for coupled multi-antenna systems”, Proceedings of 2010 European Conference on Antennas and Propagation (EuCAP), Barcelona, Spain, Apr. 12-16, 2010.

C. Chen and M. A. Jensen, “Secrecy extraction from increased randomness in a time-varying MIMO channel,” Proc. of the 2009 IEEE Global Communications Conference (Globecom), pp. 1-6, Honolulu, HI, Nov. 30-Dec 4, 2009.

Srikanth Krishnamurthy

J. Ning, T. S. Kim, S.V. Krishnamurthy and C.Cordeiro, “Directional Neighbor Discovery in 60 GHz Indoor Wireless Networks,”, ACM MSWiM 2009, Canary Islands, Spain.

E. Gelal, K. Pelechrinis, T.S. Kim, I. Broustis, S. Krishnamurthy and B. Rao, “Topology Control for Effective Interference Cancellation in Multi-user MIMO Networks,” IEEE Infocom 2010, San Diego.

E. Gelal, K. Pelechrinis, I. Broustis, S. V. Krishnamurthy, S.Mohammed, A. Chockalingam, and S. K. Kasera, “On the Impact of MIMO Diversity on Higher Layer Performance,” IEEE ICDCS 2010, Genoa.

Bhaskar Rao
A.A. Bhorkar, M. Naghshvar, T. Javidi and B.D. Rao; "An Adaptive Opportunistic Routing Scheme for Wireless Ad-hoc Networks"; IEEE

International Symposium on Information Theory, 2009

E. Gelal, K. Pelechrinis, T.S. Kim, I. Broustis, S. Krishnamurthy and B. Rao; "Topology Control for Effective Interference Cancellation in Multi-user MIMO Networks"; IEEE Infocom, San Diego, CA, 2010

Sagnik Ghosh, Bhaskar D. Rao, and James R. Zeidler; "Outage-Optimal Transmission in Multiuser-MIMO Kronecker Channels"; International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Dallas, TX, pp. 4, Dallas, TX, March 14, 2010 - March 19, 2010

Lee Swindlehurst

M. Larsen and A. Swindlehurst, “MIMO SVD-Based Multiplexing with Imperfect Channel Knowledge," In Proc. 2010 IEEE ICASSP, Dallas, Texas, March, 2010.

James Zeidler

Sagnik Ghosh, Bhaskar D. Rao, and James R. Zeidler; "Outage-Optimal Transmission in Multiuser-MIMO Kronecker Channels"; International Conference on Acoustics, Speech, and Signal Processing (ICASSP), Dallas, TX, , pp. 4, Dallas, TX, March 14, 2010 - March 19, 2010

Sheu-Sheu Tan, Dong Zheng, Junshan Zhang and James Zeidler; "Distributed Opportunistic Scheduling For Ad-Hoc Communications Under Delay Constraint"; IEEE INFOCOM 2010, pp. 9, San Diego, CA, March 15, 2010 - March 19, 2010

K. Stamatiou, F. Rossetto, M. Haenggi, T. Javidi, J. Zeidler and M. Zorzi ``A delay-minimizing routing strategy for wireless multi-hop networks," in Proc. IEEEWorkshop on Spatial Stochastic Models for Wireless Networks (SPASWIN), Seoul, June 2009

S.S. Tan, A. Anderson, and J. R. Zeidler, “The Role of Channel Distribution Information in the Cross-Layer Design of Opportunistic Schedules for MIMO Networks, Asilomar Conference on Signals Systems and Computers, Pacific Grove, CA, Nov. 2010 (selected as a finalist in the best student paper awards)

JJ Garcia-Luna

Z. Wang, M. Ji, H. Sadjadpour, and J.J. Garcia-Luna-Aceves, Cooperation-Multiuser Diversity Trade- offs in Wireless Cellular Networks, Proc. IEEE Globecom 2009 Wireless Networking Symposium, 30 Nov. - 4 Dec., 2009, Honolulu, HI.

Number of Papers published in peer-reviewed Conferences: 17

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 17

(d) Manuscripts

Submitted Manuscripts 2009-2010

Tara Javidi

A. Bhorkar, M. Naghshvar, T. Javidi, B. Rao, “An Adaptive Opportunistic Routing Scheme for Wireless Ad-hoc Networks,” submitted to IEEE/ACM Transactions on Networking, 2009

R. N. Swamy and T. Javidi, “Optimal Code Length for Bursty Sources with Deadlines, IEEE International Symposium on Information Theory, 2009

Michael Jensen

Y. Shi and M. A. Jensen, “Feedback reduction for CDI-based beamforming in the MIMO broadcast channel,” IEEE Trans. Wireless Communications, submitted Mar. 2010.

Y. Shi and M. A. Jensen, “Efficient link scheduling for MIMO ad hoc networks in time-varying channels,” Proc. of the 2010 IEEE Global Communications Conference (Globecom), submitted.

Srikanth Krishnamurthy

M. Arslan, K. Pelechrinis, I . Broustis, S. V. Krishnamurthy, S. Addepalli and K. Papagiannaki, “Bonding Together: Autoconfiguration of 802.11n WLANs”, under submission.

Laurence Milstein

Qi Qu, Laurence B. Milstein, and Dhadesugoor R. Vaman; "Cooperative and Constrained MIMO Communications in Wireless"; submitted for publication in IEEE Transactions on Wireless Communications, July, 2009

John G. Proakis

K. Stamatiou, J.G. Proakis and J.R. Zeidler, “Outage probability evaluation in random wireless networks with multiple antennas,” in preparation, September 2009.

Bhaskar Rao

Y. Isukapalli and B. D. Rao, “Multi-antenna wireless channel modeling: statistical properties and prediction,” in preparation, IEEE Transactions on Signal Processing

A.A. Bhorkar, M. Naghshvar, T. Javidi and B.D. Rao; "An Adaptive Opportunistic Routing Scheme for Wireless Ad-hoc Networks"; submitted for publication in IEEE / ACM Transactions on Networking, 2009

James Zeidler

K. Stamatiou, J.G. Proakis and J.R. Zeidler, “Outage probability evaluation in random wireless networks with multiple antennas,” in preparation, September 2009.

Kostas Stamatiou, Francesco Rossetto, Martin Haenggi, James R. Zeidler and Michele Zorzi; "Delay-minimizing Routing for Random Wireless"; submitted for publication in IEEE Transactions on Wireless Communications, April, 2009

Michele Zorzi

Kostas Stamatiou, Francesco Rossetto, Martin Haenggi, James R. Zeidler and Michele Zorzi; "Delay-minimizing Routing for Random Wireless"; submitted for publication in IEEE Transactions on Wireless Communications, April, 2009

Marco Levorato, Federico Librino and Michele Zorzi, “Distributed cooperative routing and hybrid ARQ in MIMO-BLAST ad hoc networks”, submitted to IEEE Transactions on Communications, 2009.

Davide Chiarotto, Paolo Casari, and Michele Zorzi, “On the Statistics and MAC Implications of Channel Estimation Errors in MIMO Ad Hoc Networks,” IEEE Transactions on Wireless Communications, submitted, 2010.

Number of manuscripts 11

Number of Manuscripts: 11.00

Patents Submitted

H. Jafarkhani and F. Li “A Method and Apparatus for Interference Cancellation and Detection Using Precoders.”

Patents Awarded

Awards

Yingbo Hua

Member of Editorial Board, IEEE Signal Processing Magazine, 2009
Member, Technical Program Committee, Asia-Pacific Signal and Information Processing Association (APSIPA) Annual Summit and
Conference, Sapporo Convention Center, Japan, Oct 4-7, 2009

Hamid Jafarkhani

Keynote Speaker, World Congress on Computer Science and Information Engineering (CSIE), 2009
Area Editor, IEEE Transactions on Wireless Communications
Session Chair in following conferences:
IEEE Wireless Communications and Networking Conference (WCNC), 2009
IEEE Data Compression Conference (DCC), 2009
TPC member in following conferences:
IEEE Global Communications Conference (Globecom), 2009
IEEE International Conference on Communications (ICC), 2009
IEEE Wireless Communications and Networking Conference (WCNC), 2009
IEEE Data Compression Conference (DCC), 2009

Mike Jensen

Invited Conference Presentation
Editor-in-Chief, IEEE Transactions on Antennas and Propagation, 2010-2013
Technical Program Committee Member: 2010 IEEE Antennas and Propagation Society International Symposium IEEE Antennas and Propagation Society Joint Meetings Committee Chair, 2008-2010
Associate Editor, IEEE Antennas and Wireless Propagation Letters, 2009-2010 Symposium Co-Chair, 2010 Intl. Conference on Wireless Information Technology and Systems, Honolulu, HI.

Laurence Milstein

Senior Editor, IEEE Journal on Selected Areas in Communications
Editorial Board, Journal of the Franklin Institute
TPC Co-Chair, 2009 Int. Symp. on Ultra Wideband Communications

Lee Swindlehurst

IEEE Editorial Assignments:
Editor-in-Chief, IEEE Journal of Selected Topics in Signal Processing
Member, Editorial Board, IEEE Signal Processing Magazine
Member, Editorial Board, EURASIP Journal of Wireless Communications and Networking

James Zeidler

Co-Author of best student paper award finalist for the IEEE Asilomar Conference

Michele Zorzi

Member-at-Large of the IEEE Communications Society Board of Governors
Editor-in-Chief of the IEEE Transactions on Communications
Editor for Europe of the Wiley Journal on Wireless Communications and Mobile Computing
Member of the editorial board: ACM Journal of Wireless Networks
Member of the steering committee: IEEE Transactions on Mobile Computing

Graduate Students

NAME	PERCENT SUPPORTED
Ece Gelal	0.15
Mustafa Arslan	0.15
Yan Shi	1.00
Sagnik Ghosh	0.15
Yuan Yu	0.50
Ting Kong	0.50
Seok Ho Chang	0.15
Yogananda Isukapalli	0.15
Jianxia Ning	0.50
Konstantinos Pelechrinis	0.50
Chan Chen	0.50
Kostas Stamatiou	0.15
Sheu-Sheu Tan	0.15
FTE Equivalent:	**4.55**
Total Number:	**13**

Names of Post Doctorates

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT SUPPORTED	National Academy Member
Michael Jensen	0.15	No
Srikanth Krishnamurthy	0.10	No
James Zeidler	0.50	No
FTE Equivalent:	**0.75**	
Total Number:	**3**	

Names of Under Graduate students supported

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

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The number of undergraduates funded by this agreement who graduated during this period: 0.00

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Farzad Etemadi
Siavash Ekbatani
Yogananda Isukapalli
Kostas Stamatiou
Ece Gelal
Seok-Ho Chang
Javad Kazemitabar
Yuan Yu

Total Number: **8**

Names of other research staff

NAME	PERCENT SUPPORTED	
Mark Plummer	0.15	No
FTE Equivalent:	**0.15**	
Total Number:	**1**	

Sub Contractors (DD882)

1 a. University of California - Santa Cruz

1 b. Office of Sponsored Projects
The Regents of the University of Califor
Santa Cruz CA 950641077

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Sub Contract Award Date (f-1):
Sub Contract Est Completion Date(f-2):

1 a. University of California - Santa Cruz

1 b. Office of Sponsored Projects
1156 High Street
Santa Cruz CA 95064

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Patent Clause Number (d-1):
Patent Date (d-2):
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Final Report

May, 2010

Submitted to U.S. Army Research Office

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PI: James R. Zeidler

Co-PIs: J.J. Garcia-Luna, Yingbo Hua, Simon Haykin, Hamid Jafarkhani,

Tara Javidi, Michael Jensen, Srikanth Krishnamurthy, Laurence Milstein,

John Proakis, Bhaskar Rao, A. Lee Swindlehurst, Michele Zorzi

Contact: Dr. James R Zeidler, University of California, San Diego, Department of Electrical and Computer Engineering, 9500 Gilman Dr. #0407, La Jolla, CA 92093-0407. Tel: (858)534-5369

Email: Zeidler@ece.ucsd.edu

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Sincerely,

Dr. James Zeidler
Department of Electrical and Computer Engineering
University of California, San Diego

Table of Contents

REPORT DOCUMENTATION PAGE

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6. AUTHOR(S) James Zeidler (PI), J.J. Garcia-Luna, Simon Haykin, Yingbo Hua, Hamid Jafarkhani, Tara Javidi, Michael Jensen, Srikanth Krisnamurthy, Laurence Milstein, John Proakis, Bhaskar Rao, A. Lee Swindlehurst, Michele Zorzi

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California - San Diego
Office of Contract and Grant Administration
9500 Gilman Drive, Mail Code 0934 La Jolla, CA 92093-0436

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The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

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13. ABSTRACT (Maximum 200 words)

The use of electronically steerable antenna arrays, space-time multiple input multiple output (MIMO) signal processing techniques, and improved techniques for error correction have demonstrated the capability to greatly improve the performance of point-to-point communications for both commercial and tactical networks. In this project we have addressed the challenging question of how these technological developments can best be exploited in a tactical networking context, where signal interference and channel uncertainty issues have a tremendous impact on end-to-end system performance.

Tactical applications pose unique requirements for the network, including decentralized control to eliminate single points-of-failure, vulnerability to jamming and electronic warfare, and mission critical latency bounds for end-to-end data delivery. Moreover, a tactical network is generally composed of mobile nodes and the routing protocols must deal with a range of node mobilities and time varying channel conditions. This project has focused on the design of ad hoc networking architectures that utilize MIMO transmitters and receivers at each node of this mobile, decentralized tactical network. The goal of this program has been to define the best way to utilize multiple transmit and receive antennas at each node to improve the robustness, capacity, and quality of service of the network.

14. SUBJECT TERMS	15. NUMBER OF PAGES
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Enclosure 1

Abstract

The use of electronically steerable antenna arrays, space-time multiple input multiple output (MIMO) signal processing techniques, and improved techniques for error correction have demonstrated the capability to greatly improve the performance of point-to-point communications for both commercial and tactical networks. In this project we have addressed the challenging question of how these technological developments can best be exploited in a tactical networking context, where signal interference and channel uncertainty issues have a tremendous impact on end-to-end system performance.

Tactical applications pose unique requirements for the network, including decentralized control to eliminate single points-of-failure, vulnerability to jamming and electronic warfare, and mission critical latency bounds for end-to-end data delivery. Moreover, a tactical network is generally composed of mobile nodes and the routing protocols must deal with a range of node mobilities and time varying channel conditions. This project has focused on the design of ad hoc networking architectures that utilize MIMO transmitters and receivers at each node of this mobile, decentralized tactical network. The goal of this program has been to define the best way to utilize multiple transmit and receive antennas at each node to improve the robustness, capacity, and quality of service of the network.

This report summarizes the significant advances that were achieved in this project concerning the underlying issues associated with incorporating the information available from the MIMO physical layer into the network routing and scheduling protocols for mobile ad hoc tactical networks.

1. Introduction

The specified objective of this MURI topic was to "create network protocols and signal processing algorithms necessary to implement adaptive beam steering and spatial channel reuse in mobile wireless communication networks with the specific objective of enabling reuse of radio channels to double network capacity and improve protection for military communications". The research has made major advances in satisfying the stated goal of the solicitation of providing "the science that will allow for the decision of which spatial reuse technique to use (space-time coding (STC) or transmit beam forming), if any, based on topology and network load".

The project team consists of fourteen faculty members from four campuses of the University of California (San Diego, Irvine, Santa Cruz, and Riverside); Brigham Young University, Provo, Utah; and McMaster University, Hamilton, Ontario, Canada. The individual faculty members were selected for specific areas of expertise that together spanned the wide ranging research concentration areas defined in the initial BAA for the topic area. The specified concentration areas spanned "the physics of RF propagation and signal processing; the electrical engineering of antenna array design and electronics; computer science of networking; and the mathematics of information and control theory".

It was evident from the outset that a cross-layer approach was required to fully exploit the improvements at the physical layer to optimize the capacity, robustness and quality of service for the overall network. A series of project meetings were held at UCSD and UC, Irvine over the course of the project to facilitate the interaction between experts in various aspects of the overall problem. The meetings defined a set of significant research issues and identified promising approaches to solve the underlying problems that must be addressed so that robust and reliable mobile ad hoc networks can to developed for tactical applications. These group meetings led to joint work between PIs, joint publications, co-advising of graduate students, and numerous visits between subgroups of PIs to identify viable approaches for solving specific cross-layer networking problems.

The problem definition, research issues and goals, and the research results and accomplishments were defined in the previous interim annual reports for the project and also in the extensive body of published work that the research has generated and referenced at the end of this report and posted on the project website. This work has resulted in over 35 PhD dissertations and hundreds of published journal papers, conference papers, books and book chapters on the topics related to this research.

This final report summarizes the main results and conclusions reached during the project.
We have solved some of the important MIMO antenna design issues required to achieve optimal diversity and developed techniques for exploiting beamforming (BF) and STC for improved collision avoidance. One of the difficulties in optimizing performance in realistic communications networks is that many of the important parameters must be estimated from the data. Accurate models of the time-varying channels that connect the nodes of the network are

required to maximize the network capacity. We have developed and deployed channel sounding equipment and developed MIMO channel models that describe the experimental data.

One of the fundamental issues involved in optimizing multiuser MIMO ad hoc networks is that the transmissions between any given pair of nodes in the network creates interference for other nodes in the network. Performance optimization depends on numerous parameters such as the transmit power, the number of simultaneous steams transmitted, the channel stability, the feedback delay between nodes, the number of bits fed back to the transmitter, and the packet delay in the overall network. It was shown that the network performance is optimized by utilizing the spatial processing gains afforded by the antennas to manage the interference in a controlled fashion rather than simply trying to improve existing network routing and scheduling protocols to reduce the number of collisions. Our results indicate that the full potential for the integration of the physical layer information from MIMO antennas into the routing and scheduling protocols for a tactical ad hoc network will only be achieved by utilizing the antennas to enable multiple simultaneous transmissions from multiple nodes to provide multi-packet reception capabilities at each node.

Since many of the nodes in a tactical network are mobile, the effects of Doppler spread, interleaving depths, and channel estimation errors have been included in the analysis. In addition, a variety of signaling schemes such as code division multiple-access (CDMA), frequency-hopped spread spectrum, and orthogonal frequency division multiplexing (OFDM) can be used to provide frequency diversity and code diversity to further enhance the performance of a MIMO ad hoc network. These issues are also examined in this project and the results are summarized below.

Cross-layer medium access control (MAC) protocols and routing protocols have been developed that include details of the underlying processes occurring at the physical (PHY) layer. Protocols have been developed to provide neighbor discovery and tracking in mobile ad hoc networks using polling techniques for MIMO nodes. Centralized and distributed topology control algorithms have been develop to ensure node connectivity and bounded path stretch. A framework called MUSIC that decodes multiple concurrent signals using successive interference cancellation (SIC) has been developed to provide effective interference cancellation in multi-user MIMO networks. Tests of these protocols have demonstrated the performance enhancements available from the MIMO nodes as described below.

The advantages of cooperative communications between nodes using either relay nodes and/or virtual MIMO nodes has been quantified in this project. It has been shown that these approaches provide energy efficient utilization of the network resources and enable the development of protocols with significant spatial spreading gain even for nodes with limited antenna resources. Such cooperation has also been shown to provide improved space-time scheduling in terms of fairness and quality of service.

The utilization of MIMO assets requires that the determination of maximal channel capacity in MIMO ad hoc networks must be reexamined as a function of how the information is disseminated. The use of unicast, multicast, broadcast and various forms on one-to-one, one-to-many and many-to-many routing can be done more efficiently with multiple antennas at the

nodes. Studies of the fundamental limits for the dissemination of information over mobile ad hoc networks have been completed. The optimization of the routing protocols depends fundamentally on the quality of the channel state information (CSI) that is available at the nodes of the network however, and significant effort has been made to define the best transmission strategies as a function of the available CSI. An testbed has been developed and tested to evaluate different configurations and to evaluate end-to-end performance that incorporates network quality of service (QOS) metrics such as delay and network capacity in multi-hop ad hoc networks.

The relations between MIMO signal processing and network coding have been explored and novel rate adaptation techniques that can trade off rate for coding and diversity gain have been developed. In addition network metrics such as information efficiency and throughput have been defined in terms of physical layer parameters such as the modulation and coding schemes, the channel statistics, the Doppler rate and the spatial diversity order. The selection of the appropriate number of training symbols to assure given levels of throughput, delay and efficiency were also evaluated. The dependence of the information efficiency and network throughput on the underlying physical parameters of the network was also extended to random multi-hop networks.

One of the initial barriers to crosslayer integration of the physical layer information into the routing and scheduling protocols was the significant differences between the time scales associated with the relative time scales of channel variations at the physical layer that occur at the symbol rate and the temporal stability (nominally a packet interval) that is deemed necessary for reliable routing and scheduling. Stable subspaces in the channel impulse response have been identified for which stable transmission can be sustained without instantaneous channel state information at the transmitter. This was accomplished using channel distribution information instead of CSI. The reduction in the required feedback requirements for CDI vs CSI have been quantified. The effect of quantized noisy feedback in the CSI estimates was also investigated and the concepts of network beamforming and distributed beamforming have been examined.

A summary of the major research activities conducted and results that were obtained is provided below. Detailed descriptions of the overall results are provided in the papers listed at the end of this report. In addition these papers are posted on the ARO website and also on the project website at http://zeidler.ucsd.edu/~muri

2.0 Physical Layer Considerations for MIMO Ad Hoc Networks

2.1 Antenna Design in MIMO Systems

Michael A. Jensen, Principal Investigator
Matthew Morris, Graduate Student
Nicolas Bikhazi, Graduate Student
Britton Quist, Graduate Student
Daniel Evans, Graduate Student
Daniele Pinchera, Visiting Graduate Student

Antenna design for MIMO systems presents new challenges that have not been considered in prior literature. First, while much work has been performed on antenna mutual coupling for arrays, these models have failed to incorporate the impact of noise on a receiver front-end, which is a critical consideration. Furthermore, many MIMO studies show benefits from mutual coupling, but they ignore not only the impact of noise but also the impact of impedance mismatch in general. Second, many studies on coupled antennas for MIMO have produced non-intuitive results, and we have found that this stems from physically improper transmit constraints. Applying feasible constraints, however, leads to array supergain that must be removed using practical considerations. Finally, a key question asked by antenna designers is how to design antennas that are somehow "optimal" for MIMO and diversity. Our work has focused on these issues.

2.1.1 Summary of Achievements

Papers [2], [6], [8], [10]-[13], [18], [19], [23]-[26], and [31][*] focus on the impact of antenna mutual coupling on MIMO system performance. Specifically, we were the first to provide a complete system model that incorporates both the electromagnetics of coupling and the impedance impacts associated with attaching a physical network to the array. This model also incorporates a realistic representation of the noise generated by receiver front-ends.

These models have clarified a long-term confusion in the community about the impact of coupling on MIMO systems. Specifically, in the past, the community has believed that enhanced pattern diversity associated with coupled antennas leads to improved MIMO performance. However, these studies have not considered the impact of impedance mismatch on the achieved SNR. Including these effects leads to a physically-realistic description of the coupled array. Furthermore, this study has revealed that optimal matching to a coupled array, whether for maximum power transfer or minimum front-end noise figure, requires implementation of a coupled matching network.

[*] See section 10 for references

We have also quantified the impact of using uncoupled matching networks with coupled arrays, and have derived methods to design optimal uncoupled terminations that achieve maximum power transfer or minimum noise figure. These methods have been applied to radio astronomy as well as MIMO and diversity systems.

Many studies of MIMO system performance constrain the currents that drive a transmit antenna. However, as antennas become closely spaced, this constraint does not limit the power radiated by the array. This has led to non-physical conclusions that it is always better to move antennas closer together. We have analyzed this case carefully, and have determined that this conclusion stems from the fact that for closely-spaced antennas, the radiated power increases substantially. However, if we instead constrain the radiated power, we find that the signaling solution leads to array supergain for closely-spaced antennas, something that is impractical. Papers [7], [9], [27], and [30] show methods for limiting supergain in these solutions. Specifically, we either limit the allowable array quality factor achieved, or we introduce loss into the antennas to remove the supergain solutions. This is the first observation of supergain effects in the MIMO literature as well as the first demonstration of methods to remove supergain solutions.

Papers [1], [3]-[5], [14]-[17], [20]-[22], [28]-[29], and [32] address antenna design for MIMO and diversity systems. MIMO capacity depends on the electromagnetic propagation environment as well as the antenna array used to interact with that environment. However, it is useful to understand the upper bound on capacity independent of the antenna configuration. We have formulated this solution. As a side benefit, this solution shows the optimal current distributions (antennas) that achieve the optimal capacity. However, these solutions are specific to the instantaneous channel state, and therefore the resulting antenna design is impractical for implementation.

Motivated by this observation, we have formulated an antenna synthesis procedure that considers the average behavior of the propagation environment and formulates the antennas that optimize the diversity gain for those average propagation characteristics. In the first solution to this problem, the resulting antennas were impractical, since the resulting currents describing the radiation of the individual antennas overlapped in the aperture. We then reformulated the problem for non-overlapping currents. The resulting solutions can be used as inputs into an antenna synthesis engine to enable design of near-optimal diversity antennas. This work further shows that antennas optimizing diversity gain also optimize the upper bound on the MIMO ergodic capacity for the same environment.

One important finding of this work is the significant gain achievable by antennas that can reconfigure to the current average propagation conditions. One method for implementing this configurability is the use of passive elements, coupled to the radiating antennas, and loaded with voltage-controlled impedances. Our work has demonstrated the design of such an antenna and characterized its performance using experimental measurements with our channel sounding equipment. This work has demonstrated that a two-element array with six passive elements can achieve the same capacity as a traditional two-element array with a 3-dB reduction in average power and 7.5-dB reduction in peak power. Additional work on this concept by other researchers now regularly appears in the literature.

2.2 Channel Characterization for Multiuser MIMO Ad Hoc Networks

2.2.1 Measurement and Modeling of Time-Varying MIMO Channels

Michael A. Jensen, Principal Investigator
Jon Wallace, Post-Doctoral Researcher
Chan Chen, Graduate Student

In MIMO ad-hoc networks, optimal use of the MIMO resources for maximizing network throughput requires using the spatial degrees of freedom for multi-user signaling. Effective accomplishment of this objective requires that the nodes maintain accurate channel state information (CSI), which can be challenging for mobile nodes whose channels vary rapidly in time. To understand the performance of such systems, it is critical that we have accurate models of the MIMO time-varying channel. In this work, we have experimentally investigated the characteristics of the time-varying MIMO channel in different environments and captured the observed behaviors in stochastic models. This has involved construction and deployment of a new channel sounder and development of new modeling paradigms capable of providing high accuracy with relatively low complexity.

2.2.1.1 Summary of Achievements

Papers [37] and [54] report on an experimental channel sounding system developed as part of this work. The system can measure the MIMO transfer function for 8 transmit and 8 receive antennas over instantaneous bandwidths up to 100 MHz. It uses a switched architecture to cycle through all transmit-receive antenna pairs, allowing simple calibration of the receive electronics. The switching time is programmable using a PC host, and it can switch through the entire set of antennas in as little as 64 microseconds.

This system has undergone several revisions throughout the duration of the project. At first, switch control was conducted using a custom board consisting of counters, while now it is completely controlled using an FPGA control system. The original version used a high-speed A/D card to sample the downconverted waveform. However, this approach required that we sample until we filled up memory on the card, and then we stopped acquiring data to dump this data to the PC host disk drive. More recently, we have changed the sampling architecture such that a high-speed A/D now feeds an FPGA that performs an FFT on the data. If the transmit waveform consists of multiple tones, we select the FFT outputs corresponding to the coefficients of the tones. The resulting reduction in data allows this relatively modest data flow to be stored to disk over a USB connection in real time.

This system has been deployed in indoor environments as well as urban, suburban, and forested areas. Currently, it is being modified to be flown on a helicopter to test impairments on the air-to-ground channel at several US test ranges.

Papers [38]-[43], [46], [49]-[53] all report on a variety of different results from the channel sounding campaigns. These measurement results consist of several key features. For example, while there have been many different studies that have explored the temporal characteristics of single-input single-output (SISO) channels, these metrics are difficult to apply to the MIMO channel because of its multi-variate nature. We have applied some of these traditional measures of time variation, such as level crossing rates and fade durations, to the eigenstructure of the MIMO channels. More importantly, we have developed new information theoretic metrics that quantify the loss in communication capacity as a result of using CSI acquired at one instant to communicate over a changing channel.

These results also teach that the rate of change of a channel is directly related to the multipath richness. Specifically, when the density of scatterers and the resulting multipath richness are high, the channel changes rapidly with time or node location. Areas such as urban or forested environments have particularly high rates of change. However, these studies show that while the channel changes rapidly, the spatial covariance of the channel changes slowly. Our studies show that this covariance depends on the multipath spatial structure, which varies as the angles of departure and arrival or gains of the dominant multipath components change due to node or scatterer position. This rate of change is naturally much slower than that experienced in the channel itself, since channel changes are a result of multipath *interference* effects that tend to occur on wavelength scales.

Our analysis reveals that for point-to-point MIMO communication, CSI must be estimated at the receiver every time one of the nodes moves 0.1~0.2 wavelengths and updated at the transmitter when it moves roughly 10 wavelengths. For multi-user signaling, such as broadcast channel communication, the transmitter CSI must be as accurate as that at the receiver, since in this case the signaling is relying on the transmitter's knowledge of the CSI to control multi-user interference at the receiver.

Papers [35], [36], [38], [40], [43]-[45], [47], and [48] report on the development of models that can capture the time-varying nature of the MIMO channel. Initially, we developed random matrix models whose space-time covariance matches that of the experimental data. While, this model is simple and works well in some environment, it fails to be able to track changes in the environment multipath structure. As a result, we have focused attention on the time-varying nature of the underlying multipath. Specifically, we extract the major clusters of multipath from measured data sequences, and from this data we track the change in angle of departure, angle of arrival, and gain as a function of time. We estimate the power spectral density of the resulting waveforms, whiten them, and construct probability density functions from these whitened waveforms. These density functions are then used in a model. Specifically, we generate white random variables based on the density functions, and then run these random variables through a filter (using an auto-regressive process) such that they have the correct power spectral densities. This gives us a time-varying model of the multipath that can be used to estimate channel sequences and time-varying covariance matrices.

These publications have also reported on the design of antennas for mobile environments. Our analysis suggests that arrays of directive elements (arranged to cover the full communication

space in angle) achieve the same capacity but produce significantly reduced temporal variation as an identical array with omnidirectional elements.

2.2.2. Time-Varying MIMO Wireless Channels: Estimation and Performance Bounds

A. Lee Swindlehurst, Principal Investigator
Michael Larsen, Graduate Student
Christian Peel, Graduate Student

Node mobility is the most significant factor that limits the performance gain offered by multiple antennas in a communications network, whether it be cellular or ad hoc. Highly adaptive algorithms are required that exploit data detection, channel prediction and interpolation, as well as the presence of pilot data. A major focus of our research effort has been to understand the limits of MIMO channel estimation performance in highly mobile environments, and develop algorithms that exploit all available information and achieve the best possible performance. Our results in this area are summarized in the four sections that follow.

2.2.2.1 Performance Bounds in Time- and Frequency-Selective Channels

The most common way for a receiver to obtain channel information is through the insertion of known pilots, or training data, in the transmitted signal. When the transmitter, receiver, or both are moving, the channel will exhibit temporal fading, and if the wireless system is wideband, the channel may also possess frequency selectivity. In such cases, the channel is usually estimated through training data interspersed at different times and frequency bands. Once the channel is estimated at the time-frequency locations of the pilot symbols, the estimates at the remaining times and frequencies are found using interpolation and/or extrapolation. Extrapolation in time, or prediction, is particularly useful in bridging the gap between the channel estimates and the current channel state for adaptive modulation and power control. In both channel estimation and prediction, it is useful to quantify the best possible performance that may be expected as a standard for evaluating various estimation and prediction techniques. Also, it may indicate characteristics that are useful or necessary for optimal estimation and prediction performance. We have studied the theoretical performance of pilot-based channel interpolation and prediction for frequency-selective, time-fading, wireless MIMO channels via bounds for the interpolation and prediction error of the channel. These bounds are particularly suited to MIMO orthogonal frequency division multiplexing (MIMO-OFDM) systems, a popular technique for frequency-fading wideband scenarios. Analysis of these bounds demonstrates that (1) better interpolation and prediction performance can be obtained using MIMO systems, (2) parametric channel modeling is advantageous in terms of estimation performance, and (3) correlations between model parameters are important for achieving the interpolation and prediction error bound.

2.2.2.2 Link Configuration for Optimal Performance

For fast fading channels, a key issue is the choice between coherent (training-based) or non-coherent (differential) transmission schemes. In some cases, the channel may be varying so rapidly that, once estimates are formed from the training data, the channels have changed to the point that the estimates are essentially useless. In these cases, one can only resort to differential

modulation schemes. When training data plus channel tracking/prediction can be effectively used, one must decide how often and with what power to transmit the training data. Using a simple innovations model for the time-variations of the MIMO channel, we conducted a detailed performance analysis of pilot-symbol assisted modulation (PSAM) and differential modulation MIMO techniques. Our analysis is general enough to apply to both line-of-sight and Rayleigh fading environments (or combinations of the two), and includes the effects of channel estimation error. Our analysis is able to accurately predict the high-SNR error floor that results due to the use of stale channel estimates in mobile systems. In addition, we have been able to use this analysis to predict the optimal (in terms of capacity) amount of training to use for each data block, the optimal length of a data block before re-training is necessary, the optimal allocation of power between the training and data portions of the transmitted block, and also under what conditions it is better to use differential modulation rather than PSAM. While PSAM techniques generally outperform differential modulation, they require an appropriate choice of training parameters to do so.

2.2.2.3 Power Allocation and Bit Loading with Imperfect Channel Estimates

In narrowband multiple-input multiple-output (MIMO) communication systems when the channel state information (CSI) is known perfectly at the transmitter and the receiver, and with no restrictions on codebook design, the well-known waterfilling solution maximizes information throughput given a fixed transmission power. The waterfilling solution relies on decomposing the MIMO channel into multiple parallel scalar channels via the singular value decomposition (SVD). In practice, when finite codebooks are used and perfect CSI is unavailable due to mobility and channel estimation errors, power level adaptation and bit-loading schemes are needed in order to maintain reasonable performance. To analyze this scenario, we have developed expressions that detail the impact of imperfect CSI on the signal and interference-plus-noise powers for subchannels obtained via the SVD. These expressions are used to develop subchannel power and bit allocation schemes in the presence of imperfect CSI for SVD-based multiplexing systems using M-ary quadrature amplitude modulation. In particular, using our analysis, one can determine in advance whether or not spatial multiplexing will provide any rate performance gain compared with simple beamforming solutions. In addition, approximately optimal subchannel power levels are found for the imperfect CSI scenario.

2.2.2.4 Estimation Strategies for Highly Mobile Channels

Most techniques used for channel estimation in MIMO systems rely on the assumption that the channel varies slowly enough so that it may be considered constant over a block of symbols. If this assumption holds, then known pilot symbols sent from the transmitter to the receiver may be used to estimate the channel for the block. In mobile MIMO systems, the channel coefficients change too rapidly for the effective use of block training methods. To address this problem, we developed a multiple-pass decision-directed scheme for joint channel estimation and symbol decoding in rapidly-fading MIMO channel scenarios. In this scheme, pilot symbols are superimposed with a block of data symbols at the transmitter, and the receiver uses this pilot information to iteratively optimize the channel and symbol estimates at every symbol time over the entire symbol block. The optimization is carried out over a posterior distribution which incorporates information about the channel model and noise properties. The advantage of

superimposing the pilots along with the data is the ability to use them to track the channel at the same time that the symbol decisions are made. Both a forward and a backward pass through the data are used to determine the channel track. While this approach introduces a decoding delay, it is able to successfully decode data symbols in situations where the channel coherence time is less than the symbol duration.

2.3 Impact of Quantization, Channel Estimation Errors, and Feedback Delay on Feedback MIMO System Performance and Protocol Design for MIMO AdHoc Networks with Feedback

PI: Bhaskar D. Rao
GSRs: Jun Zheng, Yogananda Isukapalli, and Abhijeet Bhorkar

Research Summary

As discussed above, knowledge of the channel state is required to optimally allocate the antenna resources to optimize network performance. This becomes a challenging problem however for an ad hoc network with a significant number of nodes and multiple antennas per node. In order to develop practical systems it is necessary to limit the amount of information that is transmitted between each pair of nodes to minimize the interference in the network and to achieve manageable processing requirements at the transmitters and receivers. In addition, the pilot tones that are transmitted to determine the CSI reduce the usable data rate for the channel and it is desirable to determine the minimum number of feedback bits required to estimate the channels. Also, the movement of the nodes in tactical networks result in changes in the channel state during the time that is required to feedback information between the nodes.

To cope with the resulting errors in channel state information and to manage the interference that results it is necessary to examine the effect of quantization, channel state estimation errors and feedback delay in order to design effective protocols for MIMO ad hoc tactical networks. Professor Rao and his students made significant advances in understanding the impact of these parameters on protocol design. Their main contributions are summarized below:

1. They developed vector quantization (VQ) based novel feedback design techniques as well as high resolution quantization theory based analytical tools to understand the impact of quantization.

2. They conducted a comprehensive analysis on the impact of feedback imperfections on feedback MISO systems and developed a general framework for capturing the three forms of feedback imperfection, i.e., estimation errors, quantization, and delay, for both spatially independent and correlated fading scenarios.

3. They proposed a novel asynchronous Media Access Control (MAC) protocol, Opportunistic MAC (OMAC), for MIMO ad-hoc networks based on closed loop minimal feedback antenna selection diversity scheme and optimum receiver combining.

We now elaborate on their research results.

2.3.1 VQ based feedback systems

This work develops a general framework for the analysis of transmit beamforming based multiple antenna systems with finite rate feedback [1,2]. Inspired by the results of classical high resolution quantization theory, the problem of finite rate quantized communication system formulated as a general fixed-rate vector quantization problem with side information available at the encoder (or the quantizer) but unavailable at the decoder. The framework of the quantization problem is sufficiently general to include quantization schemes with general non-mean square distortion functions and constrained source vectors. Asymptotic distortion analysis of the proposed general quantization problem is provided by extending the vector version of the Bennett's integral. Specifically, tight lower and upper bounds of the average asymptotic distortion are proposed. The proposed general methodology provides a powerful analytical tool to study a wide range of finite rate feedback systems. To illustrate the utility of the framework, we consider the analysis of a finite rate feedback MISO beamforming system over spatially i.i.d. and correlated Rayleigh flat fading channels [1,2,4,6]. The analysis reveals that the capacity loss of correlated MISO channels is related to that of i.i.d. fading channels by a simple multiplicative factor which is given by the ratio of the geometric mean to the arithmetic mean of the eigenvalues of the channel covariance matrix.

The analytical work is extended to the important practical problem of sub-optimal quantizers resulting from mismatches in the distortion functions, source statistics, and quantization criteria [3,5,7]. As a specific application, two types of mismatched MISO CSI quantizers are investigated: quantizers whose codebooks are designed with MMSE criterion but the distortion measure is the ergodic capacity loss (i.e. mismatched design criterion), and quantizers with codebook designed with a mismatched channel covariance matrix (i.e. mismatched statistics) [3,7]. We also consider the general distortion analysis of vector quantizers with transformed codebooks, quantization methods that have recently been suggested for CSI feedback-based multiple antenna systems with correlated channels because of their simplicity and effectiveness [5,7]. In particular, with capacity loss as an objective function, upper and lower bounds on the average distortion of MISO systems with transformed codebooks are provided and compared to that of the optimal channel quantizers.

We employed the high resolution quantization framework to study the effects of finite-rate feedback of the channel state information (CSI) on the performance of spatial multiplexed MIMO systems over i.i.d. Rayleigh flat fading channels. The contributions of this work are twofold. First, we extend the general distortion analysis of vector quantizers to deal with complex source variable. Necessary and sufficient conditions that guarantee a concise high-resolution distortion analysis the complex domain is presented. Second, as an application of the proposed complex distortion analysis, tight lower bounds on the capacity loss due to the finite-rate quantization are provided for MIMO systems employing a fixed number of equal power spatial beams. Based on the obtained closed-form analytical results, it is shown that the system capacity loss decreases exponentially as the ratio of the quantization rate to the total degrees of freedom to be quantized. Moreover, MIMO CSI-quantizers mismatched codebooks that are only optimized for high-SNR and low-SNR regimes are also

investigated to quantify the penalties incurred by the use of mismatched codebooks. In addition, the analysis is extended to deal with MIMO systems using multi-mode spatial multiplexing transmission schemes with finite-rate CSI feedback Finally, numerical and simulation results are presented which confirm the tightness of the derived theoretical distortion bounds.

2.3.2 Feedback Imperfections and their Impact

Multiple antennas can effectively minimize the negative impact of multiplicative fading in wireless communication systems by providing spatial diversity. In this part of our work we consider a spatial diversity scheme with multiple antennas at the base station. In order to achieve the optimum performance gains, i.e., to achieve both the array gain and the diversity gain, the transmitter needs to know channel information. In frequency division duplexing systems the channel information has to be feedback to the transmitter. This feedback requirement leads to various forms of imperfection. A typical practical system has three main sources of feedback imperfection, namely, channel estimation errors, channel quantization, and feedback delay. In our work we comprehensively study the impact of feedback imperfections on the performance of multi-antenna systems.

We develop a general framework capturing the three forms of feedback imperfection, i.e., estimation errors, quantization, and delay, for both spatially independent and correlated fading scenarios. In the modeling of imperfect feedback, we show that depending on the beamforming vector construction, the feedback delay error term can be known or unknown at the receiver. On the other hand, channel estimation error term is always unknown at the receiver. In a slow fading context, i.e., in scenarios where channel remains constant for the entire packet, we highlight the fact that both the estimation error term and the delay error term remain constant, with estimation error term unknown at the receiver and delay error term known at the receiver, for the entire packet while the thermal noise changes from symbol-to-symbol. For spatially independent channels, with the help of general framework, we then analytically quantify the effect of the three forms of feedback imperfection on the symbol and bit error probabilities of both M-PSK and M-ary rectangular QAM constellations with Gray code mapping. We also derive an analytical expression for the average packet error probability with BPSK signaling.

In addition, with channel estimation errors and feedback delay, for spatially correlated channels, we develop codebook design algorithms specific to the modulation format and ergodic capacity. The new optimum codebooks show an improvement in performance compared to the existing set of codebooks available in the literature. Utilizing high resolution quantization theory and assuming perfect channel estimation at the receiver, we analyze the loss in average symbol error probability for spatially independent and correlated finite-rate feedback transmit beamforming multiple input single output systems with M1xM2-QAM constellation.

We also address the issue of minimizing the negative impact of feedback delay. A natural way to combat the effect of feedback delay is channel prediction. We study the role of ergodicity in wireless channel modeling and provide an insight into when statistical channel models that employ ensemble averaging are appropriate for the purpose of channel prediction. Simulation results complement the extensive set of analytical expressions derived. We now describe our progress in these areas and highlight our specific research contributions.

a.) Spatially i.i.d Channels with Channel Estimation Errors and Feedback Delay

In this work, we present a general framework for the performance analysis of transmit beamforming for MISO systems on Rayleigh fading channels with imperfect channel feedback. The feedback imperfections are characterized in terms of noisy channel estimation at the receiver side, quantization of CSI, and feedback delay. This formulation is shown to be applicable for any linear two-dimensional modulation schemes on spatially i.i.d Rayleigh fading channels. Our analytical framework encompasses three popular MISO system models, namely, frequency-domain duplexing (FDD) systems, FDD with finite rate quantization of CSI systems, and time-domain duplexing systems. We analyze average symbol error probability and bit error probability performances of M-PSK and M-ary rectangular QAM constellations with Gray code mapping. Our numerical and simulation results show that channel estimation inaccuracy and feedback delay are more detrimental to the system performance compared to the effects of finite-rate channel quantization.

Related publications: [J1] and [C4]

b.) Spatially Correlated Channels with Estimation Errors and Feedback Delay

As described above, we have developed an extended model that captures the three forms of imperfection in a feedback based MISO system. The modeling and further analysis become complicated once the spatially i.i.d channel assumption is replaced with spatially correlated channel.

In this work, for spatially correlated channel with estimation errors and feedback delay, a model that captures estimation errors, feedback delay, and finite-rate quantization of channel is developed. A novel codebook design algorithm that is directly related to reducing the loss in ergodic capacity of a spatially and temporally correlated channel with estimation errors delay (EED) is proposed. Analysis for the loss in ergodic capacity is presented for spatially i.i.d. channels with EED. Simulation results show that the new codebook designed under the consideration of estimation errors and feedback delay clearly outperforms the codebook designed under ideal conditions. The loss analysis of spatially i.i.d channels is also validated through computer simulations.

Related publication: [J2] and [C2]

c.) Optimum Codebook Design for Minimizing the Average SEP Loss and Analysis of Loss Due to Channel Quantization

The importance of the choice of performance metric and the effect of mismatch in the channel statistics assumptions are the main focus of this work. The effect of limited feedback on the ergodic capacity is a well studied concept. Average symbol error probability (SEP), another important communication system performance metric, has received much less attention. For a limited set of constellations and for i.i.d fading channels it has been analyzed utilizing an approximation to the statistical distribution of the key random variable that characterizes the

system performance. Similar to the capacity analysis, SEP analysis for correlated channels using such statistical methods has not met with much success.

In this work we first design codebooks that are optimum for minimizing the SEP loss assuming perfect channel knowledge at the receiver. For this scenario, we then make use of the source coding based framework to analyze the ASEP loss in correlated Rayleigh fading channels with rectangular QAM constellation. The application of the source coding based framework to this problem is quite involved because of the complicated dependency of the objective function on the random variables involved as well as the nature of the constellation (M1 x M2-QAM). The impact of the performance metric on the performance on the quantizer is highlighted by comparing the performance with past quantizer designs which utilize capacity loss as a metric. The quantizer design problem in the presence of channel estimation errors is also addressed and compared to the designs that assume perfect channel knowledge at the receiver.

Related publications: [J2], [C2], and [C5]

d.) Refinement of Channel Feedback Errors: Distinction between Feedback Delay Error Term and Estimation Error Term

Multiplicative fading is a major source of performance degradation in multipath wireless environment. Channel coding and interleaving can offer some protection from the negative effects of fading. However, in some wireless systems data has to be organized into small packets, which are confined to fixed time slots, with or without interleaving. One popular example of such a system is the slotted multiple access scheme. It is important for the system designers to know the impact of fading on the performance. An important metric for studying the performance of a non-interleaved wireless packet data transmission is the average packet error probability (PEP). Packet error probability is also increasingly becoming an important quality-of-service parameter for the wireless networking community since it determines how frequently the information packet has to be re-transmitted.

Extensive analytical results quantifying the impact of fading on average symbol and error probability (SEP/BEP) are available for various modulation schemes. However, in slow fading situations, there is no mapping between the average SEP/BEP and the average PEP. Consequently knowing average SEP/BEP does not help in understanding the average PEP. Analysis of average PEP is a more complicated problem compared to the analysis of average SEP/BEP. Analytical quantification of packet error probability has received considerable attention in the literature. Closed-form expressions for PEP have been derived for the non-coherent FSK modulation. The non-coherent FSK's SEP, conditioned on the channel, is an exponential function and taking expectation of the higher powers of conditional SEP w.r.t. the fading random variable is analytically tractable. However, closed-form expressions are not available for coherent BPSK and other constellations. Conditional PEP (conditioned on a function of the wireless channel) for a scheme such as coherent BPSK results in integer powers of the Gaussian-Q function. This makes the analysis challenging because in order to derive the average PEP expression, one has to integrate the integer powers of the Gaussian-Q function w.r.t. the random variable that captures the fading environment, an analytically difficult exercise. We also note that, to the best of our knowledge, the effect of channel estimation errors on PEP has not been considered in the literature.

In this work we consider the problem of deriving analytical expressions for PEP of a multiple input single output system with various forms of practical imperfections. We later show that this problem captures various commonly interested performance analysis of wireless systems as special cases. The first form of feedback imperfection considered is channel estimation error. It is now a common practice to model the actual channel and its estimate as a jointly Gaussian random process, with an error term that is orthogonal to the channel estimate. The error term associated with a particular channel estimate is unknown to the receiver and hence it becomes part of noise when the performance analysis is carried out. If the channel under consideration is varying at symbol level, or if the performance criteria is average symbol/bit error probability, then the variance of the error term will be simply added (along with the symbol dependency) to the variance of the receiver noise resulting in an effective noise term with variance equaling the sum of variance of receiver noise and the variance of the estimation error term. In this part of the work, we also follow the standard model of joint Gaussianity between the channel and its estimate, but adapt it to the packet fading model. An important difference is that in a packet fading model the error term is constant for the entire packet while each symbol experiences a different noise sample requiring new analytical tools.

The second form of feedback imperfection we address is the delay between constructing the beamforming vector at the receiver and using it at the transmitter. Another well accepted formulation is to treat the impact of feedback delay in a manner similar to estimation errors, i.e., actual channel and its delayed version are assumed to be jointly Gaussian with an unknown (to the receiver) error term that is orthogonal to the delayed version. Since the delay related error term is unknown to the receiver, similar to estimation related error term, during performance analysis it becomes part of noise thus removing any conceptual distinction between the mismatch in beamforming due to feedback delay and estimation errors. Though much of the past work on feedback delay effectively make the delay related error term part of receiver noise, alternate options were considered (primarily in the context of adaptive modulation). However, it is important to note that much of the work treated estimation errors and feedback delay in a similar manner, i.e., either both the error terms are assumed to be known or unknown to the receiver. In this work, based on feedback system considerations we feel it is appropriate to treat the errors due to feedback delay to be known at the receiver, while the errors due to estimation errors are un-known at the receiver. This modeling approach is adopted in this work and it shows that the impact of feedback delay on beamforming MISO system performance can be less severe and is also conceptually quite different from channel estimation errors.

The third form of feedback imperfection considered in this work is finite-rate quantization of the channel. To summarize, the contributions presented in this work are threefold: an accurate characterization of estimation errors in a packet fading context, a new modeling of feedback delay which shows improved performance for a beamforming MISO system and conceptually distinguishes it from estimation errors, and derivation of an analytical expression quantifying the impact of channel estimation errors, feedback delay and channel quantization on the average packet error probability. All these contributions further the understanding of feedback communication systems. As a side benefit, the analytical tools developed promise to be of general interest with broad applicability.

Related publications: [J3], [J5], [C1], and [C3]

e.) Channel Modeling and Prediction

In all the above-mentioned work we clearly show that the effect of delay and estimation errors is detrimental to system performance. Increasing the pilot SNR of training symbols can reduce the estimation error, however delay is a serious problem and it is fundamentally different from estimation errors. To combat delay we are approaching the problem in two directions, one is prediction of the channel and the other is developing a different system model such that the delay impact is minimized. The idea behind the channel prediction is that the receiver feeds predicted version of the channel rather than the actual channel.

Following the sinusoidal channel model, conditions under which the ergodic assumption is valid are presented. This sheds insight into when statistical channel models that employ ensemble averaging are appropriate. Due to the lack of ergodicity in a typical real world wireless channel, Least Squares prediction, an approach based on time averages is motivated as opposed to linear minimum mean squared error channel prediction, an approach based on ensemble averaging then study methods such as Forward-Backward and rank reduction for high quality channel prediction.

Related publications: [C6]

2.3.4 MAC Protocols for MIMO Ad-Hoc Networks

Professor Rao and his group have also developed a MAC protocol for MIMO Ad-Hoc Networks. The use of space-time block codes in ad-hoc networks has received some attention. The advantage of such a scheme is that one can benefit from the spatial diversity without significantly impacting the spatial spectral characteristics. The use of feedback has proven to be more complex. To exploit MIMO capabilities with feedback, we propose a novel asynchronous Media Access Control (MAC) protocol, Opportunistic MAC (OMAC), for MIMO ad-hoc networks. The proposed solution is based on closed loop minimal feedback antenna selection diversity scheme and optimum receiver combining. The use of antenna selection diversity contributes to a reduction in the feedback information and in the effective interference produced. To utilize the spatial degrees of freedom offered by MIMO, we propose the use of a novel rank based metric to obtain interference information as well to enable multiple simultaneous transmissions and to make MAC decisions. The rank of the interference matrix, R_I is used as a metric. Through analysis and simulation, we found that the proposed protocol significantly outperforms 802.11 MIMO and obtained high spatial degree of freedom utilization.

OMAC exploits the opportunities of simultaneous transmissions by using a novel rank-based physical layer metric in order to maximize the utilization of the degrees of freedom in MIMO ad hoc wireless networks. Number of active transmitters in the network is an indicator of utilization of degrees of freedom. We chose rank of the correlation Matrix of interference matrix, Rank(R_I), for estimating the number of active transmitters on the channel. A node proceeds with transmission only if estimated Rank(R_I) is less than maximum supported degrees of freedom in MIMO system. The basic Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)

is at the heart of the proposed OMAC protocol. The protocol transmits RTC/CTS using Space Time Block Codes (STBC) while DATA and ACK are transmitted using antenna selection diversity.

Our initial work assumed that the rank estimation mechanism was error-free (i.e., it would always correctly estimate the number of concurrent communications). We also developed a robust method to estimate this quantity, based on a rank estimation algorithm resilient to noise and interference. Our key contribution is the design and performance evaluation of a novel carrier sense scheme tailored to MIMO that exploits the spatial structure of MIMO waveforms. The proposed carrier sense system used here is by no means specific to OMAC, and could also be adopted by other MIMO ad hoc protocols. The other MIMO MAC protocols based on carrier sense may use the conventional approach (i.e., compare the average received power across the antennas against a certain threshold) that does not exploit this structure or may propose ad hoc techniques that work only when transmissions are slot synchronous, while our scheme works also for asynchronous communications. We show that this carrier sense mechanism can help realize the communication parallelism inherent in MIMO at a limited cost in computational complexity.

2.4 Doppler Sensitivity of Channel State Estimation for Mobile Ad Hoc Networks

PI: James R. Zeidler and John Proakis
GSR: Jittra Jootar

The errors associated with node mobility were discussed above. In wireless communication systems, error-correcting codes, such as convolutional codes or turbo codes, are often used with interleavers to mitigate the fading effect and to improve the system performance. At the receiver, the maximal-likelihood (ML) decoder needs to know the fading coefficients to coherently decode the received signal; thus, the channel estimation has to be performed at the receiver. Considering the effects from both the erroneous channel estimates and the finite-depth interleaved coding as a function of the Doppler spread, there is a fundamental tradeoff in performance because fast fading improves the performance by increasing the channel diversity but concurrently degrades the performance by making the channel estimates less reliable. This results in the channel estimation-channel diversity tradeoff in the system.

In this project, we investigated the effect of the channel estimation error and the Doppler spread on the performance of finite-depth interleaved convolutionally coded systems. We developed analytic descriptions of the channel estimation-channel diversity tradeoff and verified those results with extensive simulation studies for three transmit diversity modes in the WCDMA standard, namely, no transmit diversity, the Alamouti space-time code and closed-loop mode transmit diversity (CLTD) or the closed-loop beam-forming. We analyzed each system configuration as a function of the Doppler spread of the signal produced by the mobile nodes.

The results provide insights into the tradeoff between the estimation accuracy and the channel diversity.

The performance of finite-depth convolutionally coded systems and Alamouti space-time coded system (without and without finite-depth interleaved convolutional codes) was analyzed with noisy channel estimates in time-varying fading channels. In all cases, the channel estimates were assumed to be derived from noisy pilot signals through FIR filters. The results have shown that the Alamouti linear-combining scheme, when used with ML convolutional decoder, performs very well until the Doppler spread becomes very large and interference between space-time coded symbols dominates the system performance. The ML space-time/convolutional decoder is more tolerant to Doppler spread since it does not require the quasi-static assumption. We have also compared the analytical results and the simulation results of the linear-combining scheme with the ML convolutional decoder and showed that the analysis can accurately predict the performance of the system.

We have also analyzed the performance of the closed-loop transmit diversity system (with and without finite-depth interleaved convolutional codes) with noisy channel estimates. When the closed-loop transmit diversity is used, the receiver sends back complex weights calculated from noisy channel estimates to the transmitter where these complex weights are to be multiplied to data signals prior to the transmission from multiple transmit antennas. Two sub-schemes considered are the phase-amplitude CLTD (PA-CLTD) and phase-only CLTD (PO-CLTD). In the PA-CLTD scheme the complex weights may not have the same amplitude but in the PO-CLTD scheme the complex weights must have the same amplitude (equal transmit power from the two antennas). The results have shown that PA-CLTD performs slightly better than PO-CLTD and that the performance of these systems degrades quite rapidly when the Doppler spread increases.

2.5 Increasing Temporal Stability for Multi-User MIMO Signaling Using Channel Statistics

Michael A. Jensen, Principal Investigator
James R. Zeidler, Principal Investigator
Bhaskar Rao, Principal Investigator
Adam Anderson, Graduate Student
Yan Shi, Graduate Student
Sagnik Ghosh, Graduate Student

2.5.1 Average Rate Maximization using Channel Statistics

Our work showing the impact of channel time variation on multi-user MIMO performance, particularly for the MIMO broadcast channel (BC), underscores the importance of maintaining accurate channel state information (CSI) at the transmit nodes. The sheer volume of feedback necessary to maintain this accurate transmitter CSI can make this an unreasonable goal,

particularly for mobile nodes with highly-variant channels. Motivated by our observations that the spatial covariance of the channels varies slowly in time, we sought to formulate solutions for BC signaling that provide more stable performance in time-varying channels.

Summary of Achievements

Our papers on this topic use experimental data to show that the performance of traditional signaling methods for the MIMO BC, namely dirty-paper coding and multi-user beamforming such as regularized channel inversion, falls off very rapidly as the CSI becomes stale. Specifically, if channel variation occurs due to node mobility, we find that we lose over half of the available capacity when the nodes move just 0.1 wavelengths. Naturally, errors incurred during channel estimation can have an equally detrimental impact on the throughput performance. These observations motivate the search for MIMO BC precoders that provide more robustness to channel variations or errors.

We developed a linear beamforming technique [56] that derives the transmit precoding based on the transmit covariance matrix assuming the full channel matrix can be modeled using a Kronecker product. This method achieves sub-optimal network sum rate compared to that achieved using CSI-based precoding strategies. However, by the time nodes have moved ~0.1 wavelengths, the precoding based on channel statistics, or channel distribution information (CDI), outperforms the CSI-based techniques. Furthermore, our findings show that the throughput performance remains stable for multiple wavelengths of motion (as opposed to fractions of a wavelength for CSI-based precoding). As a result, on average, it is easy to maintain much higher throughput using CDI-based beamforming with much longer intervals between feedback of channel information. Follow-on work [55] revealed a more rigorous development of the precoding based on the full covariance of the channel (as opposed to the transmit covariance matrix).

While this reduction in feedback frequency is powerful, the technique suffers from the fact that the full covariance is much larger than the channel matrix. For an $N_r \times N_t$ channel matrix, the full covariance matrix has dimensions $N_r N_t \times N_r N_t$. Therefore, the feedback frequency must be dramatically reduced to compensate for this much larger feedback complexity. To address this issue, we have developed two different methods for feedback complexity reduction. In the first technique, we assume that the full covariance matrix can be represented using the Kronecker product $\mathbf{R} = \boldsymbol{R}_r \otimes \boldsymbol{R}_t$, where the component matrices are computed from the Rank-1 approximation. We can then feed back the component matrices, which have dimensions $N_r \times N_r$ and $N_t \times N_t$. This represents a significant savings in feedback complexity.

However, this feedback reduction produces some performance loss. We have also demonstrated that the full covariance matrix can be adequately represented, at least for the purposes of constructing the MIMO BC precoder, by its dominant eigenvector and eigenvalue. Applying this approach for data compression leads to very little performance loss. Furthermore, if some additional performance loss can be tolerated, this compression can be applied to the component matrices in the Kronecker model representation. These compression techniques lead to feedback complexities that are the same as or smaller than those required for CSI feedback with dramatically reduced feedback frequencies.

2.5.2. Reducing Transmit Power based on Outage Probability

With CDI, while we can assure some average rate as defined above, we can never guarantee that a communication scheme will achieve a certain rate 100% of the time (which would require perfect CSI). In this work, we developed an outage probability framework to quantify the impact on overall network performance. In this framework, we quantify the outage on the links and guarantee a certain rate or SNR the remainder of the time. In this work an expression for the outage probability was derived and the sum power in the network was minimized subject to the constraints on the outage. This means we want each link to meet its SINR threshold *x%* of the time, where we are able to set *x*. We first looked at the single-user problem, where only the channel statistics are known at both the transmitter and receiver. Such a scenario can occur when the nodes are moving so rapidly that even the receiver has a difficult time capturing the channel. For this case we solved for the optimal transmit and receive beamformers and derived the power required to meet an outage constraint. It is shown in [64] that the acceptance of a given outage on the link, allows for significant reduction in the transmit power using CDI relative to that required for CSI.

3.0 Interference Management in Multiuser MIMO Ad Hoc Networks

A fundamental issue in optimizing the physical layer for multiuser MIMO ad hoc networks is that the transmissions between each pair of nodes creates interference for the neighboring nodes The fact that each node has multiple antennas provides the possibility for diversity gain for the link but there exist a number of different ways that this diversity can be exploited to optimize network performance. One could use the antennas to create multiple transmission paths between the nodes to provide channel diversity using transmit and/or receive diversity. In addition, a variety of signaling techniques such as Direct Sequence CDMA, Frequency Hopped spread spectrum and Orthogonal Frequency Division Multiplexing can be utilized to provide frequency diversity and/or code diversity for the signaling waveforms utilized by the network. In addition OFDM can be implemented as a multicarrier version where the subcarriers are either spread or unspread. The waveform selected will affect the diversity provided at the physical layer and the accuracy of the CSI estimates. This will be discussed in more detail in Section 4.2.

In this program we have examined a number of issues in how the multiple antennas can best be utilized to optimize performance in a multiuser MIMO ad-hoc network. The issues considered include the transmission power, the number of simultaneous streams that should be transmitted, the optimal transmission range to maximize the information efficiency, and the end-to-end delay performance for multi-hop random networks

3.1 Interference Suppression at the Transmitter in Point-to-Multipoint MIMO Transmission

John G. Proakis, Principal Investigator
James R. Zeidler, Principal Investigator
Laurence B. Milstein, Principal Investigator
Patrick Amihood, Graduate Student
Arun Batra, Graduate Student

In MIMO ad-hoc networks, it is desirable to simplify receiver design so as to minimize power consumption. For example, the receiver may not have the processing capability to suppress multiuser interference in a MIMO system. Therefore, the burden may fall on the transmitter to spatially equalize the channel. Moreover, in the presence of frequency selective fading, the transmitter must also perform temporal equalization. Precoding at the transmitter can unburden the receiver by performing joint spatial and temporal equalization. This technique is also employed in multiuser MIMO systems, where the receivers are not co-located (point-to-multipoint transmission) and, consequently, may not jointly process the signals received at different receivers.

In this work, we have investigated interference mitigation techniques in point-to-multipoint (broadcast) MIMO communication systems, in which the interference mitigation is performed at the transmitter. To mitigate the interference at the transmitter, the transmitter must know the channel characteristics, typically the channel impulse response. This channel state information (CSI) may be obtained from channel measurements performed at each of the receivers by means of received pilot signals sent by the transmitter. Then, the CSI must be sent to the transmitter. In such a scenario, the channel time variations must be relatively slow so that a reliable estimate of the channel characteristics is available at the transmitter. In some systems, the uplink and downlink channels are identical, e.g., the same frequency band is employed for both the uplink and the downlink, but separate time slots are used for transmission. This transmission mode is called time-division duplex (TDD). In TDD systems, the pilot signals for channel measurement may be sent by each of the users in the uplink. In our treatment, we have considered two cases. In the first case, we assume that the channel characteristics are known perfectly at the transmitter. In the second case, we assume that the channel measurement is corrupted by additive noise, and we evaluate the effect of the noisy estimate on the error rate performance. The transmitter is assumed to employ N_T antennas to transmit data to K receivers, where $N_T \geq K$.

2.5.1.1. Summary of Achievements

In papers [1] and [2], we have investigated a precoding method based on the QR decomposition of the channel matrix. The channel matrix is known perfectly at the transmitter and is a realization of a matrix whose entries are i.i.d. complex Gaussian random variables. The QR decomposition enables us to express the equivalent channel as an upper-right triangular matrix, thus enabling Successive Interference Cancellation (SIC). While equalization at the receiver can cause noise enhancement, equalization at the transmitter can cause the required transmit power to vary over a large range. This is due to the SIC which feeds back the spatial and temporal interference. We employ Tomlinson-Harashima precoding to limit the transmit power. This is

accomplished by a modulo operation at both the transmitter and the receiver. The signal is then transmitted over a frequency selective fading channel to geographically distributed receivers. As a result of precoding, the signals at each receive antenna see no interference due to the signals intended for the other receivers or due to the ISI.

We have obtained an expression for the conditional probability of symbol error as a function of the average SNR-per-bit, the number of transmit antennas, the number of receivers, and the number of paths between each antenna pair, and the parameter indicating the size of the square M-QAM constellation. This expression includes the effect of Tomlinson-Harashima precoding, which causes a slight degradation in performance due to the modulo operations. The effect of Tomlinson-Harashima precoding is negligible at high SNR, since the thermal noise component of the test statistic is less likely to effect the modulo operation.

To obtain the unconditional probability of symbol error, we averaged over the distribution of the squared-diagonal elements of the upper-right triangular matrix associated with the QR decomposition of the channel matrix. It is shown that these squared-diagonal elements are independent scaled chi-squared distributed random variables with different degrees of freedom.

We investigated the effect of the optimal ordering of the receive antennas. Each ordering is associated with a different QR decomposition and each decomposition requires a different transmit power. While it is possible, for a given channel matrix, to search over all possible permutations to obtain the ordering that minimizes the transmit power, and while algorithms exist that simplify this search, we approached the problem analytically, deriving the distribution of the squared-diagonal elements of the upper-right triangular matrix associated with the *optimal* QR decomposition of the channel matrix.

The key to deriving the required distribution associated with the optimal ordering, is to express the squared-diagonal elements of the QR decomposition in terms of the inner-products of the columns of the channel matrix. The inner-products are shown to be Wishart distributed. The required distribution associated with the optimal ordering reduces to an integration of the Wishart density over a complicated region. Since it is difficult to express the limits of integration explicitly, we found a closed-form expression for the probability density function of the squared-diagonal elements of the upper-right triangular matrix belonging to the optimal QR decomposition when two transmit antennas and two receive antennas are employed.

Simulations corroborated the analytical results, both for an unordered and the ordered QR decomposition. It was shown that an increase in the number of transmit antennas increases the spatial diversity available in the system. This can be explained by observing that the probability of symbol error is a function of the squared-diagonal elements of the upper-triangular matrix. Their degrees of freedom increase for an increasing number of transmit antennas. It was also shown that minimizing the total transmit energy by selecting the optimal order, results in improved performance compared to an unordered QR decomposition.

In journal paper [4], we evaluated the effects of channel estimation errors on the performance of a point-to-multipoint, multiple-antenna communication system employing Tomlinson-Harashima precoding and the QR decomposition, that transmits over frequency-flat fading channels to

decentralized receivers. The QR decomposition of the channel matrix is employed to arrive at an equivalent channel where successive interference cancellation at the transmitter can be used to remove the effect of the multiuser interference. However, in the case of imperfect channel estimation, it is not possible to remove the effect of the multiuser interference due to a mismatch between the precoder and the channel. Consequently, it is necessary to include the estimation error in deriving the probability of symbol error. We also provide simulations to corroborate the analytical results on the performance degradation due to channel estimation errors.

In papers [1], [2], and [4], the focus was on the use of the QR decomposition and Tomlinson-Harashima precoding to suppress the interference at the transmitter. This is basically a nonlinear precoding method. In conference paper [3], we consider other nonlinear precoding methods, namely vector precoding and lattice precoding, as well as linear precoding methods based on the zero-forcing and mean-square-error criteria. An assessment of the effectiveness of these linear and nonlinear precoding techniques in suppressing interference in a point-to-multipoint system is provided. Finally in Chapter 9 of the book on *New Directions in Wireless Communications Research* [5], we present a tutorial survey of interference suppression techniques in point-to-multipoint multiple-antenna systems in which the interference suppression is performed at the transmitter.

3.2 Transmission Range Optimization for Wideband MIMO ad hoc Networks

PI: James R. Zeidler
GSR: Haichang Sui

There are a number of competing wideband standards that are used in the JTRS wideband networked waveforms and the legacy military communications systems. These include direct sequence code division multiple access (DS-CDMA), Frequency Hopped (FH) CDMA and Orthogonal Frequency Division Multiple Access (OFDMA). The selection of a specific signaling scheme is required to complete any detailed cross layer design and each modulation scheme has potential advantages for different applications. Professor Zeidler focused on the use of FH-CDMA for the analysis of cross layer design issues such as the optimal transmission range. Those results are summarized below.

FH-CDMA is a desirable PHY waveform for tactical mobile ad hoc networks because of its AJ capability, LPD/LPI, and operability in non-continuous spectrum. In addition, FH-CDMA is robust to the near-far problem, while DS-CDMA requires either accurate power control or multi-user detection, which may not be practical in the MANET due to the absence of central control or a priori knowledge of interfering users' spreading sequences. For several fading models, performance comparison between FH and DS CDMA systems also favors the former in distributed multiple-access networks. Due to the multiple-access capability from FH-CDMA, design of MAC protocol can also be much simplified and issues like unfairness and throughput degradation in the CSMA/CA protocols may be alleviated, while complexity and overhead involve in spatial-division multiple-access protocols in may be reduced.

We analyzed a FH-CDMA system with multiple transmit/receive antennas and Differential Unitary Space-Time Modulation (DUSTM). A Reed-Solomon (RS) coded MIMO FH-CDMA transceiver was developed for tactical ad hoc networks with high mobility. The proposed transceiver has been shown to be robust to time-and-frequency selective fading and unknown interference, which is potentially from partial-band jamming and MAI without power control. Spatial and time/frequency diversity are achieved by DUSTM and coding/interleaving, respectively. Due to the hopping nature, interference from other users or jammers exhibit a bursty behavior. To effectively suppress such interferences, a novel receiver structure was proposed to perform joint estimation-demodulation-decoding. The proposed receiver requires no a priori knowledge about the channel and interference. Its performance in bursty interference dominated environment was shown to be robust to various practical imperfections such as the estimation error, the feedback error, and suboptimal thresholds. With the help of occasional retraining, asynchronous interference can also be suppressed. These features make it very desirable under hostile environments. The decoding error probability for Erasure Insertion based on effective SINR is derived analytically.

3.2.1 Summary of achievements

The proposed receiver exhibits a high near-far resistance that may lead to relaxed requirement on power control, an important factor in distributed, open-loop networks with moderate to high mobility. Due to proper coding/interleaving and the hopping nature of the waveform, the performance of FH-CDMA systems is limited more by the distribution of the interference than by the power of the interference. This observation may hold for other systems including OFDMA with random hopping where the SINR varies significantly in a packet. In this case, conventional cross-layer design based on the average SINR within a packet may be misleading, and fundamentally different interference management schemes should be sought. For example, one implication of the high near-far resistance on network design is that the source nodes may be allowed to reach a longer distance by increasing its transmitting power. Such a strategy may be beneficial due to the reduction of number of hops required for a packet to reach its destination without seriously harm other packet transmissions when the number of nodes in the neighborhood is small compared to the available frequency slots.

We investigated the transmission range optimization problem for random networks with the proposed coded MIMO FH-CDMA transceiver and slotted-ALOHA MAC protocol. It was shown that increasing the transmission range may increase the length per hop and reduce the number of hops for a packet to reach its destination, thus reducing the overhead associated with routing and relaying. Conversely, since the communication media is shared in a wireless network, the multiple-access interference (MAI) limits the distance over which two nodes can reliably communicate, while short transmission range reduces interference to neighbors and allows spatial reuse. The transmission range R is also related to other network design parameters such as hop length, transmit power, average number of hops, and network connectivity.

The optimization of transmission range highly depends on the PHY and channel model. Similar problems have been studied for narrow-band networks and DS-CDMA networks with static channels and simplistic PHY model without explicitly considering specific coding and

interleaving. In contrast, our work assumes detailed PHY transceiver and realistic channel models, which account for path-loss, log-normal shadowing, and Rayleigh fading. The shadowing and fading are assumed time-varying with different time-scales due to mobility and hopping. Specifically, the fading is time-varying in each dwell according to Jakes' model. The coherence time of the shadowing is assumed at the order of a dwell (fast shadowing) or a packet (slow shadowing).

In our model, the nodes in the network are assumed to be randomly distributed on the plane according to a two-dimensional Poisson process. The nodes access the channel by slotted-ALOHA protocol and FH-CDMA with random hopping patterns. Transmit power of all nodes are assumed the same to account for the absence of power control. We optimize the transmission range with respect to the so-called information efficiency, which is equivalent to the product of the link throughput and the transmission range. Intuitively, it measures the average velocity at which a bit travels in the network per unit bandwidth.

Due to hopping and the randomness of the channel, the MAI power in each dwell is a random variable, which is shown to have an alpha-stable distribution. For path-loss exponent equal to 4, the probability density function of the alpha-stable MAI power can be expressed in closed-form, thus allowing the distribution of the SIR for each dwell and the packet error probability to be derived. The optimum transmission range for maximizing information efficiency is shown to be proportional to $\sqrt{q}$ where q is the spreading gain, while it scales as $q^{1/4}$ in DS-CDMA networks without multi-user detection or power control. The fact that FH-CDMA scales better with spreading gain than DS-CDMA comes from the inherent "interference diversity" due to varying SIR level within a packet, which can be exploited by coding and interleaving to effectively suppress MAI. Such diversity is not available in narrow-band or DS-CDMA systems where the SIR is usually constant in a packet.

The trade-off between the information efficiency and the transmission range depends on various factors, including the modulation and coding schemes, receiver configuration, dwell length, order of spatial diversity, and channel statistics such as Doppler frequency and shadowing spread/speed. Effects of the aforementioned factors are studied in detail. Specifically, the following observations are obtained from our results.

- Optimum MCSs are found for different system settings by numerical analysis, which offers guidance for adaptive transmissions from a network perspective. The optimal MCS is a function of not only the transmission range but also the channel and receiver setting
- Different shadowing effects depending on the transmission range. The performance under fast shadowing is better due to higher available time diversity until the transmission range extends beyond a certain point. The resulting higher interference level can be tolerated in slow shadowing when the shadowing realization for a packet is favorable, while fast shadowing leads to inferior performance in such scenario.
- Whether the shadowing is fast or slow varying depends on both the shadowing coherence time and the dwell length.
- The network performance degrades as mobility increases. However, the degradation can be compensated by increasing the DFD feedback length.
- Both space diversity and erasure insertion are important in improving information efficiency and extending Tx range

3.2.2 Implications on Network Performance

Although the results obtained focused on transmission range and information efficiency optimization, they present a general framework of incorporating accurate PHY and realistic channel models into network design and analysis. Adapting the transmission range will affect the average number of hops involved in relaying a packet in ad hoc networks. This consequently relates to the delay and power consumption of the network. The relationship between the transmission range, data transmission time, and power consumption are important network parameters that are discussed in more detail in the sections below.

Our current results show the advantage of FH- over DS-CDMA due to the interference diversity. Compared to FH-CDMA, OFDMA achieves higher spectral efficiency by overlapping the subcarriers. However, an additional interference source in OFDMA networks with mobility is the inter-carrier interference (ICI), which arises due to Doppler frequency shift and inaccurate frequency/time synchronization. The interference diversity in OFDMA systems with hopping may also be reduced because of the cross-correlation between the ICI in different subcarriers. To achieve accurate synchronization and suppress ICI in addition to other interference is challenging and will be investigated in mobile, multiuser OFDMA networks, especially ones with high mobility and hostile jamming.

One of the difficulties in optimizing performance in realistic communication networks is that many of the important parameters must be estimated from the data. This is a challenging problem in mobile, multiuser networks, especially ones with high mobility and hostile interference. The quality of a communication link is determined by both the channel and interference characteristics. Formulation of the channel quality information (CQI) at the receiver will be investigated based on the available statistics at the receiver for practical implementations. Our published results illustrate that significant gain is observed in network level results when CQI, in the form of the effective SINR, is adaptively estimated at the receiver and used in suppressing arbitrary interference without a priori knowledge. The effective SINR is related to the statistical distribution of the fading and the interference power. Generally speaking, exploiting channel state information (CSI) yields significant gain when CSI (i.e. estimates of the channel realization) is accurate, while channel distribution information (CDI) based schemes may offer consistent performance over a long time period and can be exploited at high layers in the presence of propagation delay and lag due to network layer overhead. The use of CDI for channel estimation is discussed below.

Future research objectives include further investigating the formulation of CQI at the receiver and exploiting CQI for interference suppression and adaptive transmission/routing under different MIMO transceiver structures. Interference suppression and adaptive transmission schemes that adapt to different forms of CQI and achieve robust optimum performance will be developed. Most currently available cross-layer designs formulate and exploit forms of CQI based on the assumption that the SINR in a packet is constant and the channel is static. This is not realistic in FH-CDMA or OFDMA with random hopping. In fact, the performance of FH systems depends more on the distribution than the mean of the SINR. Our results further suggest the necessity of adapting transmission/routing based on CQI for achieving optimum

performance. Further investigation is required to extend existing cross-layer studies by accounting for such distributional information in formulating and exploiting CQI. The CQI may need to be updated as nodes change their positions or the environment varies in time. Adaptive algorithms need to be developed to track such variations and maintain accurate CQI. Efficient quantization and feedback algorithms need to be developed for CQI. Design of novel MIMO transceiver structures that adapt to the level and form of available CQI and the impact of erroneous or outdated CQI on the system performance also require further investigation.

3.3 Analysis of Performance of Interference-Limited Wireless Networks

John G. Proakis, Principal Investigator
James R. Zeidler, Principal Investigator
Kostas Stamatiou, Graduate Student

Our work on performance analysis of interference-limited wireless communication systems began with a physical-layer study of the downlink of a frequency-hopped, multiple access (FH-MA) cellular system, based on the IEEE 802.20 standard. Conference papers [1], [2], [3], and journal papers [6] are focused on the performance analysis of such a system.

Subsequently, our work focused on interference effects in ad hoc networks. In one aspect of our work, we consider a network composed of an infinite number of routes on an infinite plane. The first approach we take is to assume that each route simply consists of only one link, i.e., a transmitter (TX) and receiver (RX) at distance R. This single-hop model can be considered as a snapshot of an actual multi-hop network and allows us to evaluate the performance in terms of *single-hop metrics*, that reflect the performance benefit at the multi-hop level. Such metrics are the *network throughput*, defined as the product (spatial density of TXs) x (link throughput), which addresses the need to pack as many transmissions as possible in space; and the *information efficiency*, defined as the product (transmission distance) x (link throughput), which captures the trade-off present in a multi-hop network where, transmitting farther means a packet needs fewer hops to reach its final destination. However, for a fixed TX power, the RX signal-to-interference (SIR) ratio is lower. The single-hop approach allows the analytical evaluation of the aforementioned metrics, as a function of various physical layer parameters, such as the multiple-access (MA) scheme, e.g. frequency hopping (FH), the coding scheme, e.g. convolutional coding, and in case the nodes have more than one antenna, the multiple-input multiple-output (MIMO) technique, e.g., space-time coding or spatial-multiplexing.

Although it provides useful insight on how physical layer choices affect the link performance, the above approach has its shortcomings. It implicitly assumes that the source of communication and its respective final destination lie at an infinite distance from each other and focuses on optimizing the performance of a single link, with the hope of providing a benefit at the end-to-end level. Since the distance of the final destination or the number of hops are not specified, there are no guarantees in terms of end-to-end delay and throughput.

The second part of our work assumes a simplified – but still realistic – physical layer and focuses on evaluating the end-to-end delay and throughput over a typical network route, when the source and final destination are at a specified distance R, and a number of relays are placed on the line between them, in order to forward the packets that originate at the source. A simple link-layer protocol is considered, where, if a packet is not received correctly by a node, it is stored at the head of the queue of the previous node in the route and retransmitted at the next available opportunity. Central to our analysis is the notion of stability of the relay queues, i.e., making sure that their lengths do not become unbounded over time, and, as a result, the end-to-end delay becomes infinite. We address issues such as: determining the optimal number of relays and their placements, so that the delay is minimized and/or the throughput is maximized; the impact of imperfect relay placement on the delay; the maximum allowable MAC probability for backlogged sources and the maximum allowable packet arrival probability for non-backlogged sources such that all queues in the network are stable.

With regard to the network topology, we assume that the locations of the sources (TXs in the first model) are drawn independently according to a spatially homogeneous Poisson process of density λ and the orientation of the destinations (RXs in the first model) is random. The topology, thus the interference experienced over a link, can actually change due to mobility or, effectively, due to random access, if the network is static. In both cases, a link is characterized by its packet success probability, which is an average measure of performance, over different network topologies and channel realizations. We assume that the channel between any two nodes at distance r includes Rayleigh fading and path-loss according to the law, r^{-b}, where $b>2$ is the path-loss exponent. All nodes have the same transmit power – normalized to one – and additive Gaussian noise is disregarded, i.e., we are considering an interference-limited environment.

3.3.1 Summary of Achievements

In publications [1], [2], [3], and [6], we investigate the performance of a coherent FH Multiple Access (FH-MA) cellular system, where hopping patterns are constructed from Latin squares. Some of the patterns carry pilot symbols, which the users track to estimate the channel on the data patterns and perform coherent detection. The Latin squares construction enables us to analytically evaluate the bit error probability (BEP) over each data pattern when convolutional codes are employed for error protection. The focus of our work is to precisely determine the effect that frequency and interference diversity, ensuing from FH, have on the coded performance.

Regarding frequency diversity, it is shown that the performance can vary widely for different Latin squares. Moreover, under pilot-assisted channel estimation, a performance trade-off is observed, as an increasing frequency selectivity results in more diversity, but also more inaccurate channel state information. With respect to interference diversity, we analyze the performance when the interference power variations are perfectly known or ignored by the receiver. Our results confirm that interference tracking is important in harnessing the error correcting power of convolutional coding.

In publications [7] and [8], we explore the benefits of channel diversity in wireless ad hoc networks. Our model is that of a Poisson point process of transmitters, each with a receiver at a given distance. A packet is divided into blocks which are transmitted over different subbands that are determined by random frequency hopping (FH). At the receiver, a maximum-likelihood decoder is employed to estimate the transmitted packet/codeword.

We demonstrate that large gains in terms of network capacity are possible by combining FH during packet transmission and error correction coding of modest complexity. If L is the Hamming distance of the convolutional code employed at the TX, λ is the density of TXs and M is the number of subbands, we show that, as $\lambda / M \rightarrow 0$, the codeword error probability scales as $O((\lambda / M)^L)$. This implies that the transmission capacity scales as $\varepsilon^{1/L}$ for $\varepsilon \rightarrow 0$, where ε is the constraint placed on the codeword error probability. The preconstant depends on the geometry of the symbol constellation and is also approximately proportion to N^{α} where N is the number of antennas at the RX and $\alpha = 2/b$, where $b > 2$, is the propagation exponent. We also derive upper and lower bounds on the ergodic capacity C of the typical TX-RX link.

Practical physical layer issues are discussed such as channel estimation, power control (PC) and channel correlation. We demonstrate via simulation that, with an acceptable rate loss, the accurate channel state information (CSI) can be obtained for decoding. With respect to PC, it is shown that channel inversion can actually improve the performance, since the error correction code protects the RX from the deep faces of interferers. Finally, the impact of the channel correlation is evaluated as the number or subbands and/or the number of dwells is decreased and it is shown that the gains compared to slow FH are still significant.

Publications [4] and [5] investigate the performance of single-user MIMO techniques in the interference environment of a random network. We first consider single-stream transmission and derive an upper/lower bound to the outage/success probability in a Poisson field of interferers, when a spatial diversity order N is available at the receiver. We show that the effect of spatial diversity is to provide an approximate gain of $N^{-2/b}$ in terms of spatial contention i.e., the rate of increase of the outage probability as a function of the transmitter density, when the latter is zero.

Using a lower bound to the mutual information of the MIMO channel, we derive a lower bound to the success probability in the MIMO channel, in the presence of network interference. We show that the gain in terms of spatial contention is approximately $(N_{\text{eff}})^{-2/b}$ where N_{eff} is the arithmetic mean of the spatial diversity orders of the subchannels, if detection at the receiver is performed via zero forcing and perfect successive interference cancellation. We employ these results in order to maximize the transmission capacity over the number of transmitted streams in the small outage probability regime. It is shown that, for $b \geq 4$, it is optimal to use all transmit antennas, while, for $b < 4$, the number of streams must be judiciously chosen such that the optimal trade-off between network interference and rate increase is achieved. We also examine the case where each packet is transmitted on the same subchannel in a slot (V-BLAST) and demonstrate that transmitting a packet across the antennas (D-BLAST) yields a significant gain in terms of transmission capacity. In both cases, the transmission capacity scales linearly in the number of receive antennas.

Finally, in journal paper [9] we investigate the end-to-end delay performance of multi-hop random networks. We consider networks where each route consists of a source, a number of relays and a destination at a finite distance, and the locations of the sources and relays are determined according to independent Poisson point processes. Nodes are equipped with queues to accommodate the randomness in the delivery of a packet, which is determined by the level of the SIR over each hop. Given a TDMA/ALOHA MAC protocol, we first study an idealized network model where all routes have the same number of hops, the same distance per hop and their own dedicated relays. Assuming that a stationary regime exists for this network, we analytically evaluate the mean end-to-end delay and the throughput for backlogged and non-backlogged sources. A key point in our analysis is taking into account that the interference level over each hop, i.e., the density of transmitting nodes, depends on the packet success probabilities and vice versa. The derivation of closed-form expressions permits the optimization of the mean end-to-end delay with respect to the number and placement of the relays. The benefits of this relay selection – or routing – strategy are then verified in the original network via simulation.

If the sources are backlogged, we find that the delay is minimized if the first hop is much larger than the remaining hops, e.g., in a delay-optimized three-hop route, the first hop covers half the total distance. On the other hand, in the non-backlogged case, the delay is minimized for equidistant hops. We demonstrate that the optimal numbers of hops scale sublinearly with the source-destination distance for backlogged sources and linearly for non-backlogged sources. We also discuss stability issues in a multi-hop random network and derive sufficient conditions on the medium access probability (MAP) and the traffic load, in the case of non-backlogged sources, for the rate stability of the network.

3.4 Games-Theoretic Approaches to Minimize Mutual Interference in MIMO Ad Hoc Networks

A. Lee Swindlehurst, Principal Investigator
Matthew Nokleby, Graduate Student

Managing the mutual interference between nodes in a MIMO ad hoc wireless network is crucial to realizing its potential throughput advantages. In maximizing the data rate across its own link, a transmitter interferes with other network transmissions, decreasing the throughput possible across those links. This results in a trade-off between individual data rates and total network throughput. We have focused on finding solutions that provide a fair and efficient balance between these two competing objectives. Our approach has been to use ideas from game theory to find this balance for the problems outlined below.

3.4.1 Packet Forwarding in Ad Hoc Networks

Nodes in ad hoc networks have limited transmission power, and thus routing protocols are necessary to transmit information through the network. Since ad hoc networks by definition have no centralized control, relay nodes must individually choose whether or not they will forward others' transmissions. We have focused on the design of algorithms that allow the nodes to effectively and efficiently make forwarding decisions. This problem is complex and is often

oversimplified. In addition to the obvious tradeoff between individual power consumption and network throughput, there is also the question of network degradation. Consider a node whose power supply is critically low. If it uniformly forwards packets, it may quickly exhaust its power supply and drop out of the network. However, if it forwards packets selectively, it can be of partial use as a relay node for a significantly longer time. Non-cooperative game theoretic solutions to this problem have been found, but cooperative strategies exist that increase everyone's utility. Instead, we have developed a new approach based on the idea of *satisficing game theory*. Satisficing theory eschews individual maximization as its goal, and replaces it with a more flexible assertion: instead of purely maximizing individual utility, players may consider the preferences of others as well as their own in making decisions. They also content themselves with actions that are “good enough,” rather than demanding an optimal result. This distinction gives players the ability to extend focus beyond themselves, allowing them to balance group and individual preferences in decision-making. Such an approach is ideally suited to the packet-forwarding problem, and has been shown to allow an ad hoc network to balance power consumption and packet arrival ratios efficiently.

3.4.2 Cooperative Power Scheduling for Wireless MIMO Networks

Several different approaches have been taken for finding the optimum approach for networks of interfering links. In one approach, each source node iteratively maximizes the mutual information across its own link, assuming that the interference covariance from other users is held constant. Iterations continue until no single transmitter can improve its mutual information by changing its transmit covariance. In game-theoretic terms, this solution is a (non-cooperative) *Nash equilibrium,* and is optimal from an individual standpoint in that no single user can improve its mutual information. However, individual maximization typically leads to an inefficient solution, especially if interference is strong among links. Therefore, methods have been proposed to find source covariance matrices that maximize the *sum* mutual information through the network, rather than optimizing each link individually. However, while this method gives an efficient solution in terms of total throughput, it often results in an unfair allocation of resources. When interference is strong, the optimal solution typically shuts down weaker links so that the stronger links can transmit without interference, which may be undesirable in a wireless network.

To overcome these difficulties of inefficiency and unfairness, we have approached the problem somewhat differently. First, we divide up the transmission time into time slots over which the source nodes may use different covariance matrices, and we consider the *average* mutual information across each link. This time-varying structure allows us degrees of *temporal* freedom that can be exploited in addition to the spatial degrees of freedom allowed by the MIMO channels. We also implement a result from cooperative game theory known as the *Nash bargaining solution* (NBS). In general, the Nash bargaining solution defines a solution to a resource allocation problem that is efficient, but still considers the payoff to individual players. It assumes that players may collaborate and cooperate in making a joint decision. For simplicity, we explain the Nash bargaining solution in terms of our MIMO network problem. Our results have demonstrated that the NBS provides a very effective trade-off between network performance (sum-rate) and individual link quality.

3.4.3 Multi-User Detection in Ad Hoc Networks

We have investigated the use of multi-user detection to improve performance in MIMO interference networks. Unfortunately, while multi-user detection often allows higher data rates, it greatly complicates the problem: in addition to choosing a transmit covariance for each transmitter, we must decide which signals each receiver will detect and which data rates make such detection feasible. We have derived methods to optimize the data rates in two ways: (1) maximizing the sum throughput of the network, and (2) choosing rates based on the Kalai-Smorodinsky bargaining solution from cooperative game theory. Our results demonstrate that, while sum-rate maximization yields higher average throughput, the Kalai-Smorodinsky solution provides a superior solution in terms of fairness. Our work also demonstrates the significant performance advantage that multi-user detection can achieve when used in ad hoc networks.

3.4.4 Bargaining Solutions in the MISO Interference Channel

A common model used for describing wireless ad hoc networks at the physical layer involves assuming a collection of links that are simultaneously active and thus interfering with one another during a given time slot. The problem becomes one of allocating the resources of the network (power, beamformer weights, etc) so that a particular performance metric (e.g., overall throughput, fairness, etc.) is optimized. In this work, we have examined the MISO interference channel using cooperative bargaining theory. Bargaining approaches such as the Nash bargaining solution and the Kalai-Smorodinsky solution have previously been used in wireless networks to strike a balance between max-sum rate efficiency and max-min equity (fairness) in users' rates. However, cooperative bargaining for the MISO interference channel has only been previously studied extensively for the two-user case. We have developed an algorithm that finds the optimal Kalai-Smorodinsky beamformers for an arbitrary number of users in the general MISO interference channel setting. We also consider joint scheduling and beamformer selection, using gradient ascent to find a stationary point of the Kalai-Smorodinsky objective function. When interference is strong, the flexibility allowed by scheduling compensates for the performance loss due to local optimization. Finally, we have explored the benefits of power control, showing that power control provides non-trivial throughput gains when the number of transmitter/receiver pairs is greater than the number of transmit antennas.

3.5 The Role of Unmanned Aerial Vehicles in Ad-Hoc Networks

A. Lee Swindlehurst, Principal Investigator
Pengcheng Zhan, Graduate Student

3.5.1 Motivation

Unmanned air vehicles (UAVs) are playing increasingly prominent roles in the nation's defense programs and strategy. While drones have been employed in military applications for many years, technological advances in micro-controllers, sensors, and batteries have dramatically increased their utility and versatility. Traditionally, emphasis has been placed on relatively large platforms such as *Global Hawk* and *Predator*, but increasing attention has recently been focused

on small “mini-UAVs" (MUAVs) that offer advantages in flexibility and cost. Because of their small size, they are difficult for others to detect and track, and they are able to more easily avoid threats in the environment they fly through. As a result, they can fly at much lower altitudes, on the order of tens or hundreds of feet, and collect much more precise, “localized" data. They are significantly cheaper and easier to fly, easily carried, and can often be launched by an individual in any kind of terrain without a runway or special launching device. Due to their mobility and elevation, UAVs equipped with communication capabilities can provide important advantages to ground-based ad hoc networks. Their use in routing, medium access control, and scheduling applications has been detailed in prior work, but these studies have been primarily heuristic. In our work, we have quantified the performance benefit of using UAVs in two different wireless ad hoc network applications.

3.5.2 Summary of Results

3.5.2.1 Exploiting UAVs to Improve Ad Hoc Network Connectivity

In this project, we take a mathematical approach to positioning and flying a UAV over a wireless ad hoc network in order to optimize the network's connectivity for better Quality of Service and coverage. We assume a single UAV flying over a connected network with estimates of the positions and velocities of the network nodes. The UAV itself acts as a node in the network, and can generate, receive or forward data packets to other nodes, so as to improve the network connectivity. We have quantified four types of network connectivity for the UAV-assisted MANET problem. First, *global message connectivity* was defined as the highest possible probability of successfully propagating one message to all nodes in the network. This connectivity measure represents how well a command can be delivered to all nodes. Second, *worst-case connectivity* was defined to measure how close a network is to being divided. Third, we defined *network bisection connectivity*, which quantifies the cost of dividing the network. Finally, *k-connectivity* was defined to quantify how many nodes must fail before the network becomes disconnected. The first two types of connectivity are based on the theory of spanning trees, the third type is based on spectrum graph theory, and the fourth on the max-flow min-cut theorem and Menger's theorem. Using these four definitions, we formulated the UAV deployment and movement problems, both of which are shown to be *NP*- hard. To solve the deployment problem, we first analytically studied a two-node one-UAV case. Then, we developed a simple and heuristic algorithm with two types of initialization for optimally governing the UAV's position. Moreover, for *k*-connectivity, we proposed an algorithm for improving connectivity using Delaunay Triangulation. Finally, we developed two algorithms for determining how to adjust the velocity and direction of the UAV to optimize connectivity as the network topology changes. Our results have demonstrated that the addition of one UAV can improve the global message connectivity and worst-case connectivity by up to 109% and 60%, respectively. We have also studied the improvement in network bisection connectivity and show that *k*-connectivity can be improved by almost 1.

3.5.2.2 Exploiting UAVs as Relays in Wireless Ad Hoc Networks

We investigated the performance of a network with multiple UAVs relaying messages from ground access points (APs) to a remote basestation. We focused on various aspects of the network, including: the physical layer communication link properties, i.e., analysis of the link-level throughput of the proposed transmission scheme and the Symbol Error Rate (SER) for each AP-to-UAV link, the Media Access Control (MAC) layer handoff algorithm that the APs use to switch between different UAV relays for better performance as the network evolves over time, and the network layer UAV relay deployment problems including UAV placement and optimal motion control. Our approach differs from previous work in the assumptions made about the network, the criteria used for quantifying network performance, and the development of a closed-loop UAV heading control process that allows this performance metric to be optimized. We considered a tactical communications scenario, where a set of distributed APs in a remote area is trying to communicate with a basestation, and a team of UAVs is deployed to help establish the communication links. We assumed that, in general, the APs and UAVs have multiple antennas, and we used a channel model that allows us to account for different levels of spatial correlation at the APs and UAVs. We focused on "uplink" performance, where, "uplink" refers to communications from the APs to the UAVs. Under the above assumptions, our primary contribution was the development of a heading control algorithm for the UAV relays that maximizes the sum uplink transmission rate under the constraint that the rate for each AP is above a certain threshold. We proposed the use of the Ergodic Normalized Transmission Rate (ENTR) as the performance metric for each link, and showed that it can be approximated in such a way that the optimal UAV heading can be found in closed-form. Since the topology of the network is constantly changing due to the mobility of the APs and relays, the varying link strengths require that the APs be periodically reassigned to different relays for better performance. Consequently, we developed a handoff algorithm for the network that takes into account the special motion constraints of the UAV relays. When the current UAV configuration is insufficient to accommodate all the APs at the specified Quality of Service, we proposed a new approach for determining where to deploy a new UAV relay and how to command its motion to improve the network's ENTR.

4.0 Cross Layer Design in for Interference Limited Ad Hoc Networks

4.1 Results for Professor Hamid Jafarkhani and his group

Professor Hamid Jafarkahni, Principal Investigator

Professor Jafarkahi addressed a range of issues associated with the overall problem of providing reliable channel information to the higher layers of an ad hoc tactical network. His work can be summarized into six categories:

Summary of the most important results:

(1) Transmit beamforming for MIMO-OFDM
(2) MIMO systems using finite-rate noisy feedback
(3) Network beamforming
(4) Interference cancellation in multiuser networks
(5) Canceling interference in wireless relay networks
(6) Cross-layer design in the presence of interference

In what follows, we discuss each category separately.

4.1.1 Transmit beamforming for MIMO-OFDM

Combining the benefits of the diversity/coding gain from space-time coding and the array gain from beamforming has recently attracted a lot of attention. From a practical point of view, the transmitter channel state information is degraded by several factors in the feedback channel, e.g. the bandwidth limitation, the delay, and the noise. We consider the effects of a finite-rate feedback and the noise in the feedback link. The main contributions are:

(A) Based on a first order autoregressive (AR1) dynamic fading model, we have developed two new classes of beamforming algorithms that exploit the inter-frame correlations in the channel fading. We first introduce an algorithm based on a standard predictive vector quantization (PVQ) approach, and the resulting PVQ beamformer accomplishes superior power delivery at the receiver. However, the error performance of the PVQ beamformer is not satisfactory at high SNRs, and it also has a high implementation complexity. To resolve these issues, we have then developed a novel successive beamforming (SBF) algorithm. The new SBF scheme uses the knowledge of the previous fading blocks to aid the beamforming codebook design of the current fading block. [7],[10]

(B) We have focused on the design and evaluation of the above new transmit beamforming algorithms for the multiple-input single-output (MISO) orthogonal frequency division multiplexing (OFDM) systems. In MISO-OFDM systems, carrying out transmit beamforming requires a huge amount of channel feedback, this is because the channel state information on each subcarrier has to be conveyed from the receiver to transmitter. In order to reduce the channel feedback requirement in the OFDM system, we take the time and frequency domain correlations of the channel fading into consideration. Based on our successive beamforming technique, we have developed several classes of feedback algorithms for the OFDM systems. These new algorithms use the knowledge from the previous frame or neighboring subcarrier to aid the beamforming codebook design for the current subcarrier. Through numerical simulations, we demonstrate that the proposed algorithms require a small amount of channel feedback, yet they outperform the other existing finite-rate OFDM beamformers. [11],[12]

(C) We have introduced a novel group of space-time-frequency codes based on Multiple Trellis Coded Modulation (MTCM). These codes are originally designed without accounting for the channel spectral and temporal correlation conditions. We improve the code performance by

utilizing an augmented distance spectrum enhancement technique to serve for the wireless channels that undergo mobility and multi path fading. The performance of the new group of codes, with enhanced distance spectrum characteristics is investigated through numerical simulations. [8]

(D) We have introduced a quasi-orthogonal space-time block coding scheme over multiple antenna block fading channels. The proposed code exploits temporal diversity due to the mobile nature of the block fading channel as well as spatial diversity due to multiple antennas. Using this code, we have proposed a beamforming strategy over temporally correlated channel blocks. It is assumed that the channel undergoes Doppler frequency shift and an AR1 channel model is adopted to track the channel temporal correlation coefficients at the transmitter. Using the combination of transmit beamforming and quasi-orthogonal space-time block coding over adjacent channel blocks, we accomplish to achieve the available array gains on top of notable diversity gains and coding gains, compared to the standard solutions in the conventional wireless communication schemes. In our model, the knowledge of the channel statistics at the transmitter side is based on the approximation of the Jakes' model and does not require frequent feedback updates from the receiver. Simulation results show the superiority of our scheme to the existing coding schemes with knowledge of the channel statistics at the transmitter. [9]

4.1.2 MIMO systems using finite-rate noisy feedback

Combining the benefits of the diversity/coding gain from space-time coding and the array gain from beamforming has recently attracted a lot of attention. From a practical point of view, the transmitter channel state information is degraded by several factors in the feedback channel, e.g. the bandwidth limitation, the delay, and the noise. We consider the effects of a finite-rate feedback and the noise in the feedback link. So far, we have considered the effects of limited bandwidth in the feedback link and also the noise in the feedback link. We have considered several models for the noise in the feedback link. We consider a simple discrete memoryless channel, a finite-state channel, and a reciprocal fading channel. Also, we have considered several design criteria for optimizing the combination of beamforming and space-time coding. We consider pairwise error probability, the source distortion for transmission of multimedia signals, and outage probability as design criteria. The main contributions are:

A. Space-Time Coding and Beamforming Using Noisy Rate-Limited Feedback

We combine space-time coding and transmit beamforming over quasi-static block fading MISO channels, using quantized channel feedback. Our goal is to preserve diversity and
besides, to provide additional array gain (SNR gain) compared to conventional space-time codes. In practice, the transmitter channel state information is degraded by bandwidth limitation and noise in the feedback link. The imperfect and impaired feedback leads to drastic performance degradation unless the system is robustly designed against low-resolution and erroneous feedback information. Therefore, combining coding and beamforming must be optimized for low-rate and erroneous feedback conditions. In this work, the combining is performed using a class of constellation sets inspired from orthogonal designs and precoded STBCs which is called partly precoded orthogonal designs (PPODs). PPODs provide full-diversity with any feedback

rate, any number of transmit antennas, and any amount of feedback error. The attractive property of our scheme is that it converges to conventional space-time coding with low-rate and highly erroneous feedback and to pure beamforming with high rate and error-free feedback. Moreover, our scheme shows desirable robustness against design mismatch with respect to feedback channel specifications. [14] We also study the problem of maximizing the expected rate over a slowly fading channel with quantized channel state information at the transmitter (CSIT). This problem has been recently studied in the literature assuming a noiseless feedback link. In this work, we consider a more realistic model, where the feedback link suffers from fading, as well as the limited power allocated to the feedback signals. Our scheme considers a finite-state model to capture the fading in the feedback link. We solve the rate maximization problem with different power control strategies at the transmitter. A channel optimized scalar quantizer (COSQ) is designed to incorporate feedback in our transmission scheme. Unlike the conventional COSQs where the objective is to reconstruct the source, our proposed quantizer is designed to optimize the expected rate of the forward link. For a high quality feedback channel, the proposed COSQ performs close to the noiseless feedback case, while its performance converges to the no feedback scenario as the feedback channel quality degrades. [15]

B. Joint Source-Channel Coding for Quasi-Static Fading Channels with Noisy Quantized Feedback

When the transmitted source is multimedia information and not data, minimizing the pairwise error probability or the bit error probability is not the best design criterion. In such a case, usually a distortion measure which is appropriately picked based on the nature of the transmitted signal should be minimized. Also, the nature of the coding problem is different and the analysis looks like a rate-distortion analysis. For example, let us consider the transmission of a Gaussian source over a single-input multiple-output (SIMO) quasi-static fading channel. The goal is to minimize the expected distortion of the reconstructed signal at the receiver. We consider a delay-limited scenario where channel coding is restricted to a single realization of the channel. Channel state information (CSI) is assumed to be known perfectly at the receiver, and a zero-delay, noiseless, fixed-rate feedback link provides a quantized version of the CSI to the transmitter. An upper bound on the performance is derived and it is shown that for practical values of the channel signal to noise ratio (SNR), this bound can be achieved with a very limited knowledge of the channel quality. We show that unlike the rate maximization problems, temporal power adaptation at the transmitter provides significant gains, and the amount of the gain heavily depends on the bandwidth expansion ratio. For asymptotically high SNRs, we derive the distortion exponent of the system, defined as the slope of the expected distortion with respect to the channel SNR. We show that the distortion exponent of limited feedback is equivalent to that of superposition coding without feedback, so long as the number of quantization levels in the feedback scheme is equal to the number of the layers in the superposition coding scheme. For the finite-SNR regime, we propose an optimal and efficient numerical technique to design the feedback scheme. [17] A similar problem can be considered when the feedback channel is noisy. In this case, the goal is to minimize the expected distortion of the reconstructed signal at the receiver considering the finite rate of the feedback link and the errors in the feedback link. A delay-limited scenario is assumed where channel coding is restricted to a single realization of the channel. Quantized channel state information at the transmitter (CSIT) is obtained using a noisy,

fixed-rate feedback link and is used to adjust the transmission rate and power. A channel optimized scalar quantizer (COSQ) is designed to incorporate the effects of the errors in the feedback link. For a high quality feedback channel, the proposed COSQ performs close to the noiseless feedback case, while its performance converges to the no-feedback scenario as the feedback channel quality degrades. We show that noisy feedback does not improve the performance at asymptotically high signal to noise ratios (SNRs). Nevertheless, the numerical results for a Rayleigh fading channel show that noisy feedback provides significant gains for practical values of the SNR. [18] One advantage of such a system is that the system automatically adopts itself to the level of the noise in the feedback channel. In fact, when there is no noise, the system converges to the optimal system using a noiseless feedback link. Also, as the noise in the feedback system is increased, the system converges to an open-loop system with no feedback. In other words, one attractive property of the proposed solution is that the system automatically converges to space-time coding in the extremely poor feedback case and beamforming in the high quality feedback case.

C. Outage Behavior of Quasi-Static Fading Channels with Partial Power Control and Noisy Feedback

We investigate the outage behavior of multiple antenna slowly fading channels with resolution constrained feedback and partial power control. A fixed-rate communication scheme is considered. It is known from the literature that with error-free feedback, the power control codebook that minimizes the outage probability with an average power constraint at the transmitter has a circular quantizer structure. Moreover, the diversity gain of the system increases polynomially with the cardinality of the power control codebook. Here, we study a similar system, but within a noisy feedback channel framework. We show that the optimal quantizer structure in this scenario is still circular. With noisy feedback, using the new power control codebook, the outage performance of the system is superior to that of a no-feedback system. However, we show through asymptotic analysis that the diversity gain is the same as a no-feedback scheme. [19]

4.1.3 Network beamforming

We introduce the concept of beamforming in wireless relay networks. For a network with any number of relays and no direct link, the optimal power control is solved analytically. The complexity of finding the exact solution is linear in the number of relays. Our results show that the transmitter should always use its maximal power, but surprisingly, the optimal power used at a relay can take any value between zero and its maximum transmit power. We also consider the more practical cases in which partial channel information is available. The main contributions are:

A. Beamforming in Wireless Relay Networks

This work is on relay beamforming in wireless networks, in which the receiver has perfect information of all channels and each relay knows its own channels. Instead of the commonly used total power constraint on relays and the transmitter, we use a more practical assumption that every node in the network has its own power constraint. A two-step amplify-and-forward

protocol with beamforming is used, in which the transmitter and relays are allowed to adaptively adjust their transmit power and directions according to available channel information. The optimal beamforming problem is solved analytically. The complexity of finding the exact solution is linear in the number of relays. Our results show that the transmitter should always use its maximal power and the optimal power used at a relay is not a binary function. It can take any value between zero and the maximum transmit power. Also, interestingly, this value depends on the quality of all other channels in addition to the quality of the relay's channels. Despite this coupling fact, distributive strategies are proposed in which, with the aid of a low-rate broadcast from the receiver, a relay needs only its own channel information to implement the optimal power control. Simulated performance shows that network beamforming achieves full diversity and outperforms other existing schemes. [23]

B. Distributed Beamforming in Wireless Relay Networks with Limited Feedback

First, we consider beamforming in networks whose relays know the channel means and covariances. The question we answer is: To optimize the network performance, how much power should each relay use? Two short-term power constraints are considered: an aggregate power constraint on all relays and a separate power constraint on each relay. We generalize the distributed space-time coding scheme so that each relay can adapt its transmit power according to the partial channel information it has. When the transmit power is high, we analytically solve the relay power control problems in two-relay networks based on the pairwise error probability minimization. Simulation shows that appropriate relay power control can largely improve the network reliability, especially when the qualities of the two transmission paths are far apart. In some scenarios, lack of relay power control may cause diversity loss. [22]

Then, we consider the case of the quantized beamforming in wireless relay networks. We use the Generalized Lloyd Algorithm (GLA) to design the quantizer of the feedback information and specifically to optimize the bit error rate (BER) performance of the system. Achievable bounds for different performance measures are derived. First, we analytically show that a simple feedback scheme based on relay selection can achieve full diversity. Unlike the previous diversity analysis on the relay selection scheme, our analysis is not aided by any approximations or modified forwarding schemes. Then, for high-rate feedback, we find an upper bound on the average signal-to-noise ratio (SNR) loss and show that it decays at least exponentially with the number of feedback bits, B. Using this result, we also demonstrate that the capacity loss also decays at least exponentially with B. In addition, we provide approximate upper and lower bounds on the BER, which can be calculated numerically. Simulations are also provided, which confirm our analytical results. We observe that, for R relays, our designs achieve full diversity when $B \geq \log(R)$ and a few extra feedback bits are sufficient for a satisfactory performance in terms of the array gain. Simulations also show that our approximate BER is a reliable estimation on the actual BER for even moderate values of B. [25]

C. Single and Multiple Relay Selection Schemes and Their Diversity Orders

This work is on relay selection (RS) schemes for wireless relay networks. First, we derive the diversity of many single RS schemes in the literature. Then, we generalize the idea of RS by allowing more than one relay to cooperate. Several multiple RS schemes are proposed, which are

proved to achieve full diversity. Simulation results show that they perform much better than the corresponding single RS methods and very close to the optimal multiple RS scheme. However, the computational complexity of the suboptimal schemes is linear in the number of relays, far superior to the optimal selection, which has exponential complexity. In addition, when the number of relays is large, the multiple RS schemes require the same amount of feedback bits from the receiver as single RS schemes. [24], [29]

4.1.4 Interference cancellation in multiuser networks

The issue of interference in wireless networks has recently attracted a lot of attention. The main problem is how to let multiple transmitters communicate while the receiver can handle the interference that they generate to each other messages. We have contributed to several issues related to interference cancellation.

A. Performance Analysis of Multiple Antenna Multi-User Detection

We derive the diversity order of our proposed multiple antenna multi-user cancellation and detection schemes. The common property of our detection methods is the usage of Alamouti and quasi-orthogonal space-time block codes. For detecting J users each having N transmit antennas, these schemes require only J antennas at the receiver. Our analysis shows that when having M receive antennas, the array-processing schemes provide the diversity order of $N(M - J + 1)$. In addition, our results prove that regardless of the number of users or receive antennas, when using maximum-likelihood decoding we get the full transmit and receive diversities, i.e. NM, similar to the no-interference scenario. [33]

B. Multiple-Antenna Interference Cancellation and Detection for Two Users Using Precoders

Also, we consider interference cancellation for a system with two users when users know each other channels. The goal is to utilize multiple antennas to cancel the interference without sacrificing the diversity or the complexity of the system. Before, in the literature, it was shown how a receiver with 2 receive antennas can completely cancel the interference of two users and provide a diversity of 2 for users with 2 transmit antennas. We propose a system to achieve the maximum possible diversity of 4 with low complexity. Our main idea is to design precoders, using the channel information, to make it possible for different users to transmit over orthogonal spaces. Then, using the orthogonality of the transmitted signals, the receiver can separate them and decode the signals independently. We analytically prove that the system provides full diversity to both users. In addition, we provide simulation results that confirm our analytical proof. [35], [36]

4.1.5 Canceling interference in wireless relay networks

In another effort, we consider the problem of interference in wireless relay networks. There have been many cooperative schemes proposed for relay networks. Most of these schemes are designed for a single user. We consider a relay network that allows multiple users transmit simultaneously. Our main contributions are:

A. Interference Cancellation in Distributed Space-Time Coded Wireless Relay Networks

We consider the interference cancellation (IC) problem in multi-user wireless relay networks. First, it is shown that using distributed space-time coding (DSTC), the multiple antenna IC scheme that we had proposed for systems with direct transmissions can be applied to relay networks. The ML decoding after full IC can be performed symbol by symbol. Then, by allowing IC at relays, a new degree of freedom in relay network design is discovered. With this new idea, the required number of antennas at the receiver for full IC can be reduced and a balance between diversity and delay can be obtained. [34]

B. Beamforming in Wireless Relay-Interference Networks with Quantized Feedback

We consider quantized beamforming in wireless amplify-and-forward (AF) relay networks. We use the Generalized Lloyd Algorithm (GLA) to design the quantizer of the feedback information and specifically to optimize the bit error rate (BER) performance of the system. Achievable bounds for different performance measures are derived. First, we analytically show that a simple feedback scheme based on relay selection can achieve full diversity. Unlike the previous diversity analysis on the relay selection scheme, our analysis is not aided by any approximations or modified forwarding schemes. Then, for high-rate feedback, we find an upper bound on the average signal-to-noise ratio (SNR) loss and show that it decays at least exponentially with the number of feedback bits, B. Using this result, we also demonstrate that the capacity loss also decays at least exponentially with B. In addition, we provide approximate upper and lower bounds on the BER, which can be calculated numerically. Simulations are also provided, which confirm our analytical results. We observe that, for R relays, our designs achieve full diversity when $B \geq \log R$ and a few extra feedback bits are sufficient for a satisfactory performance in terms of the array gain. Simulations also show that our approximate BER is a reliable estimation on the actual BER for even moderate values of B. [37]

4.1.6 Cross-layer design in the presence of interference

In another effort, we consider the problem of cross-layer design in the presence of interference. The ultimate goal is to cancel the interference in the physical layer instead of avoiding it in the MAC layer. As a first step to achieve our ultimate goal, we have studied the effects of interference in existing scenarios. The main contributions are:

A. Global Optimal Routing, Scheduling and Power Control for Multi-hop Wireless Networks with Interference

We consider the problem of joint routing, scheduling and power control in multi-hop wireless networks. We use a linear relation between link capacity and signal to interference noise ratio in our formulation. In a previous work, using a duality approach, the optimal link scheduling and power control that minimizes the total average transmission power is found. We formulate this problem as a linear programming problem with exponential number of constraints. To cope with the exponential number of constraints, we propose an iterative algorithm based on the cutting plane method. The separation Oracle for the cutting plane algorithm turns out to be an element-wise concave optimization problem that can be effectively solved using the branch and bound

algorithm. We extend the same method to find the optimal routing scheduling and power control. Simulation results show that this methodology is more efficient and scalable compare to the previously proposed algorithm. [28]

B. A Study of Connectivity in MIMO Fading Ad-Hoc Networks

We investigate the connectivity of fading wireless ad-hoc networks with a pair of novel connectivity metrics. Our first metric looks at the problem of connectivity relying on the outage capacity of MIMO channels. Our second metric relies on a probabilistic treatment of the symbol error rates for such channels. We relate both capacity and symbol error rates to the characteristics of the underlying communication system such as antenna configuration, modulation, coding, and signal strength measured in terms of Signal-to-Interference-Noise-Ratio (SINR). For each metric of connectivity, we also provide a simplified treatment in the case of ergodic fading channels. In each case, we assume a pair of nodes is connected if their bi-directional measure of connectivity is better than a given threshold. Our analysis relies on the central limit theorem to approximate the distribution of the combined undesired signal affecting each link of an ad-hoc network as Gaussian. Supported by our simulation results, our analysis shows that (i) a measure of connectivity purely based on signal strength is not capable of accurately capturing the connectivity phenomenon, and (ii) employing multiple antenna mobile nodes improves the connectivity of fading ad-hoc networks. [26]

4.2 Results from Professor Laurence Milstein and his group

Professor Laurence Milstein, PI
Students: Qi Qu, PhD, Andrew Ling, PhD, S-H Chang

4.2.1 Tactical Ad Hoc network performance

Research Overview

One of the largest components of our research was on tactical, mobile, ad-hoc networks. On the tactical side, this meant the anti-jam considerations were foremost in the design and performance evaluation of the systems, in particular with respect to the need for the waveforms to incorporate the use of spread spectrum signaling. The fact that the networks were mobile meant that the effects of time diversity had to be traded off with the effects of imperfect channel state information. And because the networks had to be ad hoc (to avoid a singular point of failure), algorithms for distributed resource allocation (e.g., power and rate) played a central role in the research.

There are three key papers that resulted from this research. One has been published, a second has been accepted for publication, and the third is still under review. In [1], we consider a multihop network where the effect of a queuing delay at some node along the route of a given message is countered by allowing the transmitting node to increase its power so as to skip over the congested node and thereby reduce the packet delay. The price for the increased transmit power is an increase in the interference level that is imposed upon the surrounding users, and in [1] we

address that problem with a combination of power control and rate control. Other topics addressed in this paper include the effect of intentional interference, and a tradeoff between noisy channel estimates due to mobility with the advantage of enhanced time diversity.

In [2], we extend the ad hoc network to cognitive radio, whereby to account for the military context of the scenario, we define primary and secondary users in a different manner than what is done for a commercial scenario. In our case, any user currently active is a primary user, any user not currently active in the system is a secondary user, and a primary user who leaves the system at some point is time, but wants to return to the system at a later point in time does so as a secondary user. A completely distributed resource algorithm is used, and performance results are shown that include the effect of intentional jamming.

In [3], we further extend our results to allow users of the ad hoc network to form a virtual MIMO system. The key distinction in our work relative to most of the existing literature is that we account for energy consumption in both the system setup, meaning the process of establishing precisely which users are to become members of the virtual MIMO, as well as the energy consumption of the actual transmission. Further, this research is done under delay constraints, total energy constraints (meaning constraints that account for energy expended both in the local setup and in the data transmission), and data rate constraints.

Key Results

One of the key result from this body of research was that for sufficiently accurate channel state information (CSI), an ad-hoc network, a distributed resource allocation scheme can be implemented that does not require a large amount of information to be transmitted over a control channel (i.e., much of the required information can be obtained locally at each mobile terminal), even in the presence of jamming. This, of course, has to be qualified by noting that it places limitations on the Doppler spread, for a fixed SNR, and also on the ratio of jammer power to signal power, for a fixed spread bandwidth.

Another key result is that the use of a virtual MIMO system can significantly enhance performance, but only if the cooperating mobile units are judiciously chosen, both in terms of the number of such units and specifically which ones they are. This is especially true with either tight delay constraints or tight energy constraints.

Regarding the cognitive radio-based ad hoc network, we found that by using node cooperation during the sensing mode and an efficient distributed power control algorithm during the data transmission mode, the degradation due to both the effects of random loss of bandwidth and intentional jamming, while serious, can be made graceful.

4.2.2 The Effect of Channel Estimation Errors

4.2.2.1 Research Overview

A second major topic that permeated much of our research effort was the effect of imperfect CSI. This component affected both the physical layer waveform design and the MAC layer scheduling protocol, and included both SISO and MIMO links. We chose two types of multicarrier waveforms, whereby one waveform is more sensitive to imperfect CSI than is the other waveform, but the former waveform provides more diversity than does the latter one. At the MAC layer, the tradeoff was between two scheduling schemes, one of which required accurate CSI and the other of which did not use CSI.

There were three journal papers that resulted from this research, and all have been published. In [4] and [5], we addressed the problem of the proper choice of the physical layer waveform for use in a hostile environment. We assumed that a multicarrier waveform is most appropriate, especially for systems where available bandwidth is not necessarily contiguous, such as cognitive radio. The comparison we addressed is the performance of a multiple carrier direct sequence CDMA (MC DS CDMA) system with a multicarrier CDMA (MC CDMA), that is, one that does not spread the spectrum of each subcarrier. Reference [4] pertains to a SISO system, and reference [5] extends the results of [4] to a MIMO system where Alamouti coding is used to achieve spatial diversity.

More specifically, in [4] and [5], when viewed in the frequency domain, these two multi-carrier schemes differ in the widths of their sub-bands---MC-DS-CDMA uses direct sequence spreading at each sub-carrier, while each sub-carrier in MC-CDMA is unspread. Thus, over a given bandwidth, MC-CDMA employs a larger number of sub-carriers than MC-DS-CDMA. If both schemes transmit at the same information rate, then each data symbol is repeated across a larger number of sub-carriers in MC-CDMA than in MC-DS-CDMA. While this implies that MC-CDMA potentially has higher frequency diversity than MC-DS-CDMA, it also means that if both schemes use the same energy-per-bit, then the energy per sub-carrier is lower in MC-CDMA than in MC-DS-CDMA. In other words, each MC-CDMA sub-carrier operates at a lower signal-to-noise ratio (SNR), which implies that the receiver's estimate of the channel gain at each sub-carrier frequency in MC-CDMA is more prone to error. Therefore, when MC-DS-CDMA and MC-CDMA are compared under equal bandwidth, information rate, and energy-per-bit constraints, there exists between these two schemes a possible trade-off between diversity and channel estimation errors. The introduction of MIMO considerations, in the form of Alamouti coding, into the above tradeoff, as is done in [5], further accentuates the tradeoff, because now there is spatial diversity present as well as frequency diversity.

In [6], we concentrated on the effect that mobility has on the ability of the system to obtain accurate estimates of the state of the channel. We used a multiuser-diversity scenario, taking into account the feedback errors due to channel variability. Channel estimation errors are modeled as Gaussian random variables with variance depending on the Doppler spread. Based on a block fading channel model, we present an expression for the throughput, both as a function of the key system parameters, such as packet length and data rate thresholds, and channel characteristics, such as Doppler spread.

4.2.2.2 Key Results

Consider first the SISO case of [4]. If the coherence bandwidth of the channel equals the bandwidth of one of the MC-DS-CDMA subcarriers, and if there is more than a single user active in the system, then with the same data symbol transmitted across all the subcarriers, MS-DS-CDMA outperforms MC-CDMA for all values of Eb/No. If multiple symbols are transmitted in parallel, MC-DS-CDMA yields better performance unless a sufficiently large number of pilot symbols are employed, in which case MC-CDMA has an advantage. Alternately, if the coherence bandwidth of the channel equals the bandwidth of one of the MC-CDMA subcarriers, the two systems perform the same if the multipath intensity profile is rectangular. If the multipath intensity profile is a decaying function of delay, then the MC-CDMA system outperforms the MC-DS-CDMA system.

For the MIMO case of [5], we considered only the scenario where the coherence bandwidth of the channel equaled the subcarrier bandwidth of the MS DS CDMA waveform. The results showed that for lower data rates, MC-DS-CDMA performed better than MC-CDMA in both the single- and multi-user cases for practical SNR values and number of pilot symbols used in each channel estimate, Q_P. For higher data rates, we obtained a trade-off similar to the one observed in our previous comparison between the two systems, where we considered the single-input single-output case with only one transmit and one receive antenna; that is, in the single-user case, there existed an SNR value γ_t such that MC-DS-CDMA gave a lower bit error rate for SNR values less than γ_t, while MC-CDMA performed better for SNR values greater than γ_t. This shows that the effects of channel estimation errors dominate at low SNR, while the effects of diversity dominate at high SNR.

Regarding the use of scheduling to provide multiuser diversity in a mobile environment, the desirable effects of multiuser diversity tend to disappear as the relative velocity between the transmitter and the receiver becomes large. More specifically, we compared the throughput of multiuser diversity with that of round robin. It was found that at sufficiently high Doppler, round robin performed better than did multiuser diversity.

4.2.3 Receiver Design for Sources Having Multiple Importance Classes of Symbols

In various applications, such as image and video transmission, the sources are encoded in such a way that certain bits are much more important than are other bits. For such scenarios, the use of unequal error protection (UEP) is very useful in enhancing system performance. The research in which we are engaged in this area is currently ongoing, and this section will summarize the status of that work. References [7] and [8], both of which have been submitted for publication, describe that work in detail, where [7] corresponds to our initial work for a SISO system, and [8] shows how we used MIMO to enhance the system.

4.2.3.1 Research Overview

In [7], two packetization techniques to achieve unequal error protection using hierarchical QAM are designed. In the first, an even number *N* of 16-QAM hierarchical constellations having different minimum distances are ordered from largest minimum distance to smallest. A

progressive bit stream is parsed so that the two most important bits are combined with the two least important bits to produce a point on a hierarchical constellation which uses the largest and the smallest minimum distances. Next the second two most important bits are combined with the second two least important bits, and mapped to a constellation designed with the second largest and second smallest minimum distances. This process is repeated until the entire packet is mapped. This technique can easily be extended to scenarios where there are multiple classes of importance, meaning each symbol in a given class has the same importance level. In the second scheme, an *asymmetric* hierarchical constellation is used, and bits are again mapped to constellation points by combining bits from the *i*th most important group with bits from the *i*th least important group.

The research in [8] is still in progress. In our initial research, we emphasized progressive image encoding. Among other results, we proved the following for a two-by-two MIMO system: We consider two ways of operating such a system, one designed to yield spatial diversity by Alamouti coding, and the other designed to yield spatial multiplexing. If the former system is used in conjunction with an M-QAM system having alphabet size $M = m^2$, and the latter system uses an M-QAM system with $M = m$, where m is an integer ≥ 2, then both systems transmit at the same bit rate. Under high signal-to-noise ratio conditions, and equal average power, if the bit error rates (BER) of the two systems are set equal to one another, then for SNRs above the SNR that yields equal performance, the diversity system yields a lower BER, and for lower SNRs, the multiplexed system yields a lower BER. Further, the crossover point increases monotonically as the alphabet size M increases, and the BER at the crossover point decreases monotonically as M increases. Note that this technique results in a different tradeoff between spatial diversity and spatial multiplexing than is classically the case. Spatial diversity typically yields better performance, and spatial multiplexing typically yields higher data rates. In our formulation, the data rates are the same, and spatial diversity only yields better performance when the average SNR on the channel exceeds a certain threshold.

For video transmission, note that while the base layer of a scalable video contains the most important information, it does not require large amounts of information. In contrast, the enhancement layer is less important but has more bits than the base layer. Thus, based upon the insights described above, we will use a low alphabet size in conjunction with Alamouti coding to transmit the base layer, and a high alphabet size in conjunction with spatial multiplexing to transmit the enhancement layer. Lastly, we will complement the MIMO with the UEP that comes naturally with the use of hierarchical modulation. The key attribute of hierarchical modulation in this proposal is its ability to provide different levels of protection to data having different levels of importance (such as the base layer and the enhancement layer of scalable video). Specifically, the system design that we propose precludes the possibility of a nearest neighbor error event causing an error in the more-important data class (i.e., the base layer).

As an example, for 2 by 2 MIMO systems, the constellation symbols of our scheme are given by

$$\begin{bmatrix} S_A[2n] & S_A[2n+1] \\ S_B[2n] & S_B[2n+1] \end{bmatrix} = \begin{bmatrix} x_1[2n] + x_{2A}[2n] & -x_1^*[2n+1] + x_{2A}[2n+1] \\ x_1[2n+1] + x_{2B}[2n] & x_1^*[2n] + x_{2B}[2n+1] \end{bmatrix} \quad (1)$$

where each row corresponds to a transmit antenna, each column corresponds to a time symbol, $S_A[n]$ and $S_B[n]$ are hierarchical constellation symbols which are transmitted on antennas A and B, respectively, $x_1[n]$ is the basic subconstellation symbol which is transmitted using an Alamouti code, and $x_{2A}[n]$ and $x_{2B}[n]$ are secondary subconstellation symbols which are transmitted using spatial multiplexing on antennas A and B, respectively. Note that from (1), we are effectively using fourth order diversity for the two base layer bits of each 64 QAM symbol, and using spatial multiplexing for the four enhancement layer bits of each 64 QAM symbol.

4.2.3.2 Key Results

In [7], when the BER is dominated by the minimum Euclidian distance, we proved that there exists an optimal multiplexing approach which minimizes both the average and peak powers. While the suggested methods achieve multilevel UEP, the peak-to-average power ratio (PAPR) typically will be increased when constellations having distinct minimum distances are time-multiplexed. To mitigate this effect, an asymmetric hierarchical QAM constellation, which reduces the PAPR without performance loss, was designed. We also considered the case where multiplexed constellations need to have constant power, either due to the limited capability of a power amplifier, or for the ease of cochannel interference control.

In [8], we evaluated the performance of the proposed hierarchical 4/64 QAM scheme using the mapping of (1). Note that over each symbol duration, the proposed scheme transmits 2 bits for the base layer and 8 bits for the enhancement layer (recall that we are using spatial multiplexing for the enhancement layer). For comparison purposes, we also evaluated the performance of a hierarchical 2/32 QAM scheme which employs just spatial multiplexing, and a hierarchical 4/1024 QAM scheme which employs just spatial diversity. It can be seen that both schemes also transmit 2 bits for the base layer and 8 bits for the enhancement layer during each symbol duration. In other words, the above three schemes all have the same data rate.

To compare the image quality, we use peak-signal-to-noise ratio (PSNR), a common quality measure in image compression. All three schemes are decoded using maximum likelihood decoding. As an example of the type of improvement possible, consider a Rayleigh fading channel where the average SNR on the channel is anywhere in the range 25 to 30 dB. Then the improvement in PSNR achieved by using the proposed technique is between 2 dB and 3 dB.

Note that this PSNR improvement can be directly traded off for a decrease in transmission rate, for the same level of performance. This, in turn, will lead to an increase in capacity. Indeed, given the tremendous strain that the use of video transmissions is putting on the capacity of wireless networks, this latter interpretation of the results may be the most important one.

4.2.4 Multicode MIMO in Mobile Ad-Hoc Networks

In this work, we investigated a multicode (MC) multiple input multiple output technique that can be employed to achieve high data rates in mobile ad-hoc networks. It is well known that spatial multiplexing using multiple transmit and receive antennas (V-BLAST) can be used to increase data rates without requiring additional bandwidth, but requires that the number of receive antennas at a given node must be greater than or equal to the sum of the number of transmit

antennas in all its neighbor nodes. This limits the achievable spatial multiplexing gain (data rate) for a given node.

4.2.4.1 Research Overview

For the above scenario, we proposed achieving high data rates per node by employing multicode direct sequence spread spectrum techniques in conjunction with spatial multiplexing. In the proposed multicode V-BLAST system, the receiver experiences code domain interference (CDI) in frequency selective fading, in addition to space domain interference (SDI) experienced in conventional V-BLAST systems. Accordingly, we proposed interference cancelling receivers that employ a linear parallel interference cancellation (LPIC) approach to handle the CDI, followed by a conventional V-BLAST detector to handle the SDI. RAKE combining at the LPIC output is also proposed to reduce complexity. We analyzed the bit error rate performance and the complexity of the proposed detectors.

4.2.4.2 Key Results

In [9], we analyzed the performance of multiple receiver structures that had different levels of complexity, and hence correspondingly performed differently. In all cases, the goal was to use the MC waveform to compensate for the limited degree of spatial multiplexing per node in the MIMO system. If a higher complexity receiver can be tolerated, our results showed that the use of multicode signaling and spatial multiplexing, combined with parallel interface cancellation, can outperform the conventional V-BLAST-type of multiplexing.

4.3 Results from Professor Yingbo Hua and his Group

Yingbo Hua, Principal Investigator
Ting Kong, Graduate Student
Yuan Yu, Graduate Student

Professor Hua has focused on the following major questions: 1) How should we exploit the channel diversity of spatially distributed nodes to enhance the network throughput? 2) How should we design medium access control (MAC) protocols for large-scale networks with full or varying load? 3) How should we design space-time processing methods for multi-antenna relays? We have found important answers to these questions.

For the first question, we recognized its importance at the beginning of this MURI project [C1], [C2], [C3], [C4], [C6], and it has received increasingly more attention and more research efforts by other researchers. We found that cooperation among neighboring nodes to exploit small scale channel fading is feasible and beneficial. It improves the throughput, power efficiency and network lifetime. The space-time block codes developed for multi-antenna transmitters can be used by distributed transmitting nodes, which form a virtual antenna array. Synchronization errors among the distributed nodes can be substantially mitigated by applying space-time block

codes as well. We have developed a complete family of quasi-orthogonal space-time block codes [J15] and a super-efficient differential space-time code [J16] important for dynamic mobile networks.

For the second question, we have explored the issue of maximizing the pre-constant of capacity scaling law of large-scale networks by using practically feasible MAC protocols. We have studied the effects on the pre-constant due to channel fading, multiple antennas, transmission distance, traffic loading conditions, etc. We have found that for fully loaded large networks, synchronized array method (SAM) is practically feasible and substantially outperforms other MAC protocols such as ALOHA and carrier sense multiple access (CSMA). We have also found that the transmission distance should be chosen depending on the network load. For fully loaded network in terms of bits per second per hertz per node, transmission or routing between nearest neighbors is the best strategy. But this is not true for very lightly loaded networks (again in terms of bits per second per hertz per node). For quantified insights, see [J1], [J3], [J4], [J8], [J10], [C8], [C9], [C11], [C13], [C14].

For the third question, we have discovered an optimal structure of power allocation for MIMO relay systems of two or any number of hops. We have developed space-time power scheduling algorithms for cooperative network of distributed MIMO links. We have compared centralized resource allocation schemes with decentralized resource allocation schemes including the game theory based schemes. One important conclusion is that fast power allocation is critically important for tactical mobile ad hoc networks. While a good power allocation can provide a substantial advantage of network throughput, the computation of it is generally not straightforward. This problem compounds in dynamic environment where power allocation must be fast adaptive. Our work shown in [J5], [J6], [J7], [J9], [J11], [J12], [J13], [J14], [C7], [C10], [C12], [C15] testifies strongly the importance of further research in this direction.

5 Network protocol design for next-generation ad hoc networks

Principal Investigator:	Michele Zorzi
Other contributors:	Paolo Casari, Marco Levorato, Francesco Rossetto, Andrea Munari, Elena Fasolo, Davide Chiarotto, Federico Librino

5.1 PHY characterization, PHY/MAC cross-layer design, and routing in MIMO ad hoc networks

Introduction and Motivation

One of the main objectives of the MURI project is to provide in-depth understanding and effective design criteria for next generation ad hoc wireless networks. To increase the capacity of

a wireless channel, multi-user detection was identified as a very promising technique. To correctly exploit the potential of multiuser detection in ad hoc networks with multiple antennas one needs to envision and study cross-layer MAC and routing protocols that hinge on a sufficiently detailed awareness of underlying PHY-layer processes and leverage on this information to obtain good performance at higher layers: such objectives can be successfully achieved using cross-layer design criteria, where different, and usually non-interacting, layers are steered into collaboration and mutual information passing.

Studied problems and summary of achievements

The study has started from a large-scale evaluation of Multiple-Input-Multiple-Output (MIMO) receivers aimed at understanding their performance in typical network-like contexts [MZ31][MZ30]. Different transmission schemes, including diverse combinations of digital modulation and coding strategies, have been considered [MZ30]. By including in such evaluation the transmission of packets whose length is typical of signaling as well as data transmissions, it has been possible to answer relevant questions, such as how many simultaneous signaling/data packets can be received in a typical networking scenario, and which network- and physical-layer parameters it is important to take into account in order to make effective decisions as to the management of transmissions [MZ11].

Based on these considerations, a Medium Access Control (MAC) protocol based on framed channel access has been developed and tested in a custom network simulator [MZ11][MZ31]. The protocol was specifically designed to leverage on the degrees of freedom of a multi-antenna system in two ways: by allowing for spatial multiplexing at any transmitter (thus increasing the raw bit rate of a transmission) and by providing multiuser detection capabilities at the receiver, which can exploit it to improve the level of diversity of incoming signals, and spatially de-multiplex them in a decision-feedback and successive interference cancellation fashion; among other advantages, this allows to identify potentially harmful interfering signals, so that they can be explicitly detected and canceled, instead of just being withstood as a detrimental contribution to SNR [MZ11][MZ31]. Within the scope of the protocol, different policies were identified that drove network nodes to different behaviors, and the most convenient among those were identified.

In a first phase of the work, every network operation has been modeled by detailing the transmission of every symbol of every packet [MZ11][MZ31]. However, given the high complexity of any detailed reproduction of physical layer processing algorithms in network simulators, it has become necessary to figure out an approximate representation [MZ29][MZ23][MZ19] of physical-layer performance by means of synthetic figures such as specifically defined Signal-to-Interference-and-Noise Ratios (SINRs) where noise and interference from concurrent transmissions are approximated as Gaussian processes [MZ23][MZ19] with mean and variance derived from the context (number of interfering signals, average received signal power, etc). These terms appear as detrimental contributions along with other terms specific of the multiuser detection case, i.e., the average interference power caused by wrong cancellations (which have a chance of doubling the interference of the current signal on subsequent signals in the receiver-side detection stack), and the average power of signals which are waiting to be cancelled, or perhaps cannot be canceled (e.g., to save receiver processing power). This approximate approach

has been applied to network simulation, and its results have been compared to those of more complex network simulations [MZ19], where the behavior of protocols and signal processing algorithms is reproduced in detail, and the transmission of each symbol of every packet is correspondingly modeled and accounted for. Other approximations than the Gaussian one have also been considered [MZ19][MZ29]: however, the Gaussian approximation leads to the most accurate prediction of network protocol performance. In order to optimize the behavior of the protocol and improve the overall understanding of parameter choices, a study on the effect of backoff policies has been carried out [MZ28]; an investigation of a different signaling scheme building on the one considered so far has been considered as well [MZ26]. Building on the knowledge gathered to this point, the work on this topic has been carried out along two different directions: one has dealt with routing and the integration between routing and MAC; the other has focused on modeling the effects and consequences of channel estimation inaccuracies.

In order to test routing protocols, a larger network than employed in MAC experiments was considered, so that multihop routes could be formed [MZ13]. Over this network, we tested a static routing protocol (designed according to the minimization of the number of hops given a genie-like knowledge of the network topology) against a dynamic routing protocol, designed to incorporate MAC concepts into the choice of next hops along a path. In more detail, one of the fundamental parameters beneath MAC operations is an estimate of the number of simultaneous signals a certain receiver is able to handle when addressed by a certain transmitter. This is called the class of the receiver (with respect to that transmitter). This class can be designed according to different criteria: e.g., it can depend on the average received power (which directly influences the quality of multiuser reception) and thus be determined once and for all in a static network; otherwise, and more conveniently, it can be made a function of other, time-varying performance figures such as the reliability of the receiver. This time-varying class can then be combined with other metrics such as queue backlog length, advancement provided, and so forth, in order to yield a summary of the utility brought by the choice of a certain receiver as a relay of the message being forwarded. Results show that this last choice yields good improvements over static routing in both a Poisson traffic scenario and a different scenario where traffic generation is correlated in time (a harder case, which requires good routing choices to cope with the bursts of traffic being generated).

Finally, the last part of the work on this topic has been directed towards removing the assumption that channel estimation is perfect [MZ12][MZ15][MZ2][MZ31]. Given that multiuser detection with decision-feedback successive interference cancellation hinges on the accuracy of channel estimation, this study is important for assessing the robustness of the designed network protocols to non-ideal working scenarios. A thorough model has been deployed in order to find the variance of channel samples obtained by training the receiver through a known preamble sequence [MZ12][MZ2]. While channel estimation through training sequence correlation or MMSE is a fairly well known approach, the novelty of the investigation is to consider that incoming signals usually bear different average incoming powers, but these powers can be group-wise equal. In other words, it is very likely that some signals, perhaps transmitted by the same node, arrive at the receiver with the same average power, and that this power can instead vary significantly across different transmit nodes, depending on their distance: this is especially true in a MIMO ad hoc network. Results show that the performance of protocols is negatively affected by inaccurate channel samples and even more so if the accuracy

is very low (i.e., for low training sequence lengths); however, the designed protocols can still support a certain amount of network throughput, though less than with perfect channel estimation. By making the training length for signaling and data packets vary independently, we have also highlighted an interesting interplay between PHY parameters and MAC-level performance metrics, and shown that there exists a tradeoff among such metrics: this tradeoff can be tuned by varying the length of the training sequences [MZ12][MZ15][MZ2][MZ31].

5.2 Cooperation in MIMO ad hoc networks: signaling schemes, protocols and strategies

Cooperative communication schemes

Introduction and motivation

Cooperation has been proved as a fundamental technique to improve the performance of wireless networks. By providing channel diversity to communications, cooperation mitigates the effects of channel impairments due to fading dips and thus increases the achievable rate of end-to-end communications in the network. Moreover, relays may be closer to the destination of a packet, thus providing a transmission channel with improved average received power with respect to the direct channel between a source and a destination. However, whereas cooperative techniques have been widely studied in simple point-to-point topologies, a clear understanding of the impact of the introduction of a cooperative behavior on the whole network operation is still missing. Rather intuitively, cooperative behaviors may interact with networking mechanisms and statistics. In MIMO wireless networks, communications may be operated simultaneously due to the intrinsic resilience of the physical layer architecture to interference. In this context, cooperation may influence the overall network interference load, as well as the statistics of the interference process. The study described in the following envisions cooperation as an effective mechanism to increase the efficiency of MIMO wireless networks. More specifically, the cooperative mechanisms implemented automatically selects efficient transmission configurations which also reduces the impact of an established link in terms of interference on other ongoing communications.

Studied problems and summary of achievements

The study has been divided into two phases. The first phase [MZ14][MZ21][MZ32] investigates the implementation of cooperative Hybrid Automatic Retransmission reQuest (HARQ) in single-hop MIMO wireless networks. The second phase [MZ1][MZ20] propose an extremely flexible and efficient integration of the protocol studied in the first phase with routing mechanisms. The study has been carried on by testing the proposed protocols in a simulator which models the operations of the entire network from the performance of the considered transmitter-receiver architecture to the Medium Access Control and Routing layers.

As introduced before, the first step has been to carefully design single-hop communications. Similarly to the case studied in Section 0, in the MIMO network considered in this study, multiple sources are allowed to superimpose their signals. This in order to increase the aggregate rate of the network and fully exploit the potential of the MIMO physical layer. However, unless specific communication structures are predisposed (see Section 0), the simultaneous deployment of multiple communications results in an increased channel variability due to the start and end of interfering transmissions. Error control thus becomes critical to guarantee reliability and preserve the efficiency of the communications. In order to effectively cope with the high variability of the channel conditions, a cooperative HARQ has been designed which provides the adaptive transmission of incremental redundancy packets by multiple nodes (i.e., the original source of the packet and relays). The protocol reacts to failure events due to excessive interference or fading dips by scheduling the transmission of incremental redundancy by the source and the relays. The coding rate is, therefore, adapted to the instantaneous interference/channel conditions. Cooperation, by providing simultaneous transmission of redundancy related to the same packet from multiple sources, generally shortens the duration of the communications in the network, thus reducing the overall interference load. However, a beneficial balance between interference generated and redundancy sent is obtained only if the number of relays helping a communication is kept below a certain threshold.

The second phase provided the integration of the cooperative mechanism described above with opportunistic routing. The aim is to maximize the effectiveness of the packet forwarding in multi-hop MIMO network. It can be observed that traditional routing protocols may be not effective in a network where channel conditions quickly and unpredictably vary. In fact, route formation cannot deal with the quick oscillations of the channel quality, and may fail to select an efficient sequence of relays to reach the destination. In order to cope with these issues, a cooperative protocol, referred to as cooperative HARQ and opportunistic routing (CHOR) protocol in the following, has been proposed that manages packet forwarding by adaptively and opportunistically selecting an efficient route to the destination. Note that an inefficient route, where each hop requires the transmission of a large amount of redundancy to deliver the packet to the next routing relay, may increase the interference load of the network and damage other communications by increasing both their failure rate and their waiting time before packet transmission.

The CHOR protocol combines the cooperative HARQ protocol described before with opportunistic routing. In particular, it opportunistically switches to a different next hop relay in order to minimize the amount of redundancy sent and to guarantee a geographical advancement to each packet. In the single-hop cooperative mechanism developed in the first phase, the relays transmit incremental redundancy in order to strengthen the chosen route to the destination. In the cooperative integrated error control and routing protocol proposed in the second phase of the study, those nodes may opportunistically take charge of packet forwarding in order to grant an efficient advancement of the packet toward the destination. Detailed simulations of the entire network have shown that the proposed protocol improves the aggregate performance of the network with respect to the non-cooperative version of the protocol, as well as with respect to cooperative HARQ or opportunistic routing alone.

5.3 Deafness prevention and MIMO Network Coding

Introduction and motivations

Further advancements in the study of feasible communication schemes for MIMO ad hoc networks have been made by studying the following problems:

1) The issues due to directionality in multi antenna MANETs have been addressed, with special emphasis on the problem of deafness. The result of this effort is a MAC protocol specifically designed to overcome the problems of deafness when directional communications are possible. The features of real-world signal processing algorithms have been considered so as to design a protocol that mirrors the actual limitations and advantages of antenna arrays
2) The integration of MIMO signal processing and Network Coding has been explored for the first time, leading to important performance improvements. This research line has established fundamental parallels between MIMO and Network Coding and has shed some light on limits of classic Network Coding for wireless networks. Starting from this point, novel rate adaptation techniques that can trade off rate for coding and diversity gain have been developed. Moreover, cooperative protocols based on these ideas have been successfully developed.
3) The proposal of a novel practical system for decode-and-forward physical layer network coding, a topic to which increasing effort has been devoted by the research community in the past four years. While remarkable improvements have been carried out from a theoretical point of view, the definition of practical architectures have not yet received as much attention. In this field, all issues that would hinder implementation have been virtually solved by mixing some well-known techniques (such as OFDM) and new ideas (network demodulation) in the right context

Studied problems and summary of achievements

In the first research area, the goal has been the design of strategies that may reduce the extent of the problem of deafness in ad hoc networks with directional antennas and prevent its effects. Deafness is caused by the missed reception of control packets (especially RTS/CTS) that hamper the virtual carrier sense mechanism. This problem may arise every time a node does not have an accurate perception of the state (i.e., busy/idle) of its neighbors. The use of directional transmissions/receptions exacerbates the issue by trying to exploit spatial reuse while not spreading information on the ongoing communications through the network. Protocol solutions that deal with deafness and gain asymmetries in ad hoc networks have been proposed and evaluated in [MZ6][MZ16][MZ22][MZ24][MZ25].

In the second research area, the connections between Network Coding (NC) and MIMO have been investigated. Network Coding is a decade-old technique that enables significant performance improvements in wired, multihop networks. Its main feature is to allow

intermediate nodes not only to forward received packets, but also to transmit functions of these packets. Any node can recover the original packets (called Information Units) as long as a sufficient number of their combinations (called Coded Packets) has been received. If the Coded Packets are linear combinations of a set of Information Units, the receiver has to solve a linear system to decode the original packets. This mechanism was proved to be very efficient for networks whose links are error-free. However, wireless communications by no means satisfy this property. One of the key problems is that conventional NC can use only packets that have been correctly decoded by PHY. However, if too many Coded Packets are lost, the system of equations to solve may be underdetermined, in which case decoding becomes impossible. On the other hand, a similar problem to NC is solved in MIMO systems: in a V-BLAST based communication scheme, the receiver tries to decode a vector of transmitted symbols out of a vector of received samples, and these two quantities are linked by means of a matrix. However, one of the critical features of MIMO is its resilience to channel fading. The aim of this research has been to draw a parallel between MIMO detection and NC decoding, with the final goal of improving NC robustness to wireless channel impairments. This goal is supported by analytical studies: these studies suggest that since every Information Unit is embedded in potentially all Coded Packet, a high diversity order may be achievable in this setting, because every received packet has information about the original frames. The resulting concept of MIMO_NC has been proposed and its performance evaluated in [MZ18][MZ17][MZ7]. A new cooperative protocol that is based on the MIMO_NC concept has been proposed and studied in [MZ9][MZ5][MZ10].

In the third research area, Prof. Zorzi’s efforts on network coding have focused on designing new techniques that better integrate Network Coding with the physical layer, around the idea of physical layer network coding [MZ33][MZ34]. This concept has lately attracted a certain interest in the network coding community. The basic idea can be illustrated in the two-way relay channel (TWRC). Two nodes (A and B) must exchange two packets (A's X and B's Y) through an intermediate relay R. In classic Network Coding (NC), A would send X in time slot 0, B would transmit Y in slot 1 and R would broadcast $X \oplus Y$ in slot 2. In physical layer network coding, A and B would simultaneously send X and Y, while R would relay a function of X and Y, which is invertible in X or Y as soon as the other variable is known. Given that A and B know their own packets, they can each potentially decode the other node's frame. This method reduces the number of required slots from 3 to 2. Note that R need not decode X and Y separately, but it is enough to directly decode a linear combination Z. This can potentially reduce the error rate because less information needs to be extracted from the received signal.

At least two main ideas have been developed in this context. The first one is called amplify-and-forward physical layer network coding (AF-PNC, also called analog network coding). The relay amplifies the analog superposition of X and Y and broadcasts this signal, that will be called S. The end-user terminals A and B can recover the signal sent by the other node by subtracting their own waveform out of the received signal sent by R. The resulting signal depends only on the intended packet, under the hypothesis of perfect cancellation. On the other hand, in decode-and-forward physical layer network coding (DF-PNC), R decodes a linear combination L of X and Y directly from the analog superposition. This packet L is broadcast and A and B can remove their own frame from L to recover the desired data unit.

Such systems are of interest in the context of ad hoc MIMO wireless networks for a variety of reasons. First of all, the presence of multiple antennas at the terminals is not precluded, although most of the current studies focus on single antenna terminals. Even in the presence of single-antenna terminals, the processing at the receiver is inherently MIMO, where the multiple input/output relationships are generated by the network coding technique rather than by multi-element antennas. Actually, the introduction of multiple antennas at R can dramatically improve the performance of DF-PNC: DF-PNC suppresses the noise at every decoding step. Hence, it is able to work at higher SNR than AF-PNC. Clearly, the higher the diversity, the smaller the bit error rate. Hence, the introduction of multiple antennas at least at the relay can significantly enhance the performance of DF-PNC over AF-PNC. It is thus of great interest to explore practical architectures for DF-PNC, since they would benefit more than other competing systems from the properties of MIMO techniques. Prof. Zorzi's efforts have focused on SISO nodes as a necessary and preliminary step towards MIMO nodes, but studies of MIMO centric DF-PNC are a natural extension.

6 Neighbor Discovery, Topology Control, and Cross-Layer Protocol Design

MURI Final Report
PI: Srikanth V. Krishnamurthy
Students Supported from this MURI grant:

1. Gentian Jakllari (Now with BBN Technologies)
2. Ece Gelal (Now in a software company in Seattle)
3. Ioannis Broustis (Now with Alcatel Lucent)
4. Konstantinos Pelechrinis
5. Jianxia Ning

Collaborators within the MURI
Bhaskar Rao, Michele Zorzi, Lee Swindlehurst, Michael Jensen, John Proakis, Jim Zeidler.
Collaborators outside the MURI
O. Ercetin (Sabanci University, Turkey), P. Krishnamurthy (U. Pittsburgh), M. Faloutsos (UC Riverside), S.K. Kasera (U. Utah), A. Chockalingam (Indian Institute of Science), Neal Young (UC Riverside), T. Salonidis (Thompson Resarch) and P. Mohapatra (UC Davis).

6.1 Neighbor Discovery and Topology Control in Directional Antenna Equipped Networks

Neighbor discovery and maintenance with fully directional communications is a challenge. Neighbor nodes can move out of a node's angular range and thus, they need to be tracked. However, tracking incurs overhead and can thus degrade performance. We have designed PMAC -- a MAC protocol that integrates a neighbor discovery and tracking mechanism along with the medium access control. PMAC is the first MAC protocol that uses only directional communications. As such, it overcomes the problems due to asymmetry in range and deafness – two major problems faced by all the previous MAC protocol designed for directional antennas.

The key idea that forms the basis for our protocol is the use of a polling strategy wherein a node polls its discovered neighbors periodically; this would enable the node adjust its antenna weighting coefficients so as to continuously track its neighbors. The protocol design allows for modifications to facilitate its use when space-time codes or more sophisticated antenna arrays are used. The major intricacy of the integration between the routing protocol and PMAC is topology control. This is because PMAC performs best when each node maintains links only with a minimal number of selected neighbors; other neighbors are to be reached via these chosen direct neighbors. By thus imposing a limit on node degree, we impose a bound on the polling overhead. On the other hand, in terms of routing, the effect of reducing the node degree can result in a disconnected network, or can boost the lengths of paths between nodes. We have designed centralized and distributed topology control algorithms that provide bounded node degree, while guaranteeing connectivity and bounded path stretch. The work on this topic appears in [1], [4], [5], [9] and [10].

6.2 Design of cross layer protocols with Virtual MIMO

Space-time communications can help combat fading and hence can significantly increase the capacity of ad hoc networks. Virtual MIMO links facilitate spatio-temporal communications without actually requiring the deployment of physical antenna arrays. Our motivation for investigating the deployment of virtual MIMO within the current project comes from the belief that the provision of a framework for space-time communications for already deployable networks can be crucial for the success of real MIMO based systems. Furthermore, investigating virtual MIMO links first fits within our general bottom-up approach. Virtual MIMO links allow for an easier and cheaper implementation - no additional hardware is required. Many challenges that arise while building a framework to use virtual MIMO links are very similar to those that arise when real MIMO links are to be employed. However, there exist some differences; we will further investigate these in future efforts.

We have designed protocols to exploit virtual MISO links in mobile ad hoc networks. Our approach is based on the development of a synergy between the layers of the protocol stack; lower layers export appropriate information and optimization “handles” to higher layers, while higher layers allow for the refinement of the performance parameters of lower layers. In particular, we take advantage of the extended range possible with virtual MISO links to establish shorter paths (either unicast or broadcast), which in turn, leads to an increase in throughput and a reduction in latency.

First, we develop a new MAC protocol that closely ties in with the underlying physical layer to enable virtual MISO links. In particular, the MAC layer facilitates coordination between the collaborating nodes that transmit jointly on a virtual MISO link. Second, we design a routing protocol that can construct a path with virtual MISO links. Our approach has two attractive properties: (a) it is completely decentralized and nodes do not need more than local (one-hop) information, and (b) it provides robustness to link failures due to both mobility and interference effects. The latter property is facilitated via a dynamic anycast mechanism for establishing virtual MISO links. Finally, we design efficient broadcasting techniques for use with virtual MISO links.

We perform extensive simulations with physical layer models that include fading effects to evaluate our approach. We observe that our schemes can successfully help form and exploit virtual MISO links and significantly outperform their SISO counterparts. The work done under this effort appears in [2],[3],[6] and [8].

6.3 Design and Deployment Considerations for High Performance MIMO Testbeds

MIMO (Multiple Input Multiple Output) enabled systems are characterized by higher reliability and transmission rates, as compared to conventional SISO (Single Input Single Output) systems. However, unless administered properly, the MIMO technology may not facilitate very high throughputs on point-to-point wireless links. Therefore, it becomes imperative for the network architect to design such networks in ways that fully exploit the inherent properties of MIMO. We conduct an extensive experimental study, using a powerful hardware platform, in order to understand the behavior of MIMO links in different topological scenarios. Our experiments involve scenarios with MIMO links in isolation, as well as in competition with other MIMO and SISO links. Second, we perform measurements with different commercial platforms towards assessing the ability of each platform to efficiently support the MIMO technology. Based on our experimental observations we deduce that the CPU processing speed of the underlying hardware platform is an important factor that can hide the performance benefits of a MIMO enabled tranceiver. We examine the applicability of the different hardware choices that we test; furthermore, we suggest the most appropriate choice for building a MIMO testbed, taking into account the cost, the extendability and the re-usability of the selected platform. Finally, having adopted this choice in our testbed design, we provide a description of our testbed architecture. This work appears in [12].

6.4 Topology Control for Effective Interference Cancellation in Multi-User MIMO Networks

In Multi-User MIMO networks, receivers decode multiple concurrent signals using Successive Interference Cancellation (SIC). With SIC a weak target signal can be deciphered in the presence of stronger interfering signals. However, this is only feasible if each strong interfering signal satisfies a signal-to-noise-plus-interference ratio (SINR) requirement. This necessitates the appropriate selection of a subset of links that can be concurrently active in each receiver's neighborhood; in other words, a sub-topology consisting of links that can be simultaneously active in the network is to be formed. If the selected sub-topologies are of small size, the delay between the transmission opportunities on a link increases. Thus, care should be taken to form a limited number of sub-topologies. We find that the problem of constructing the minimum number of sub-topologies such that SIC decoding is successful with a desired probability threshold, is NP-hard.

Given this, we propose MUSIC, a framework that greedily forms and activates sub-topologies, in a way that favors successful SIC decoding with a high probability. MUSIC also ensures that the number of selected sub-topologies is kept small. We provide both a centralized and a distributed version of our framework. We prove that our centralized version approximates the optimal solution for the considered problem. We also perform extensive simulations to demonstrate that

(i) MUSIC forms a small number of sub-topologies that enable efficient SIC operations; the number of sub-topologies formed is at most 17 % larger than the optimum number of topologies, discovered through exhaustive search (in small networks). (ii) MUSIC outperforms approaches that simply consider the number of antennas as a measure for determining the links that can be simultaneously active. Specifically, MUSIC provides throughput improvements of up to 4 times, as compared to such an approach, in various topological settings. The improvements can be directly attributable to a significantly higher probability of correct SIC based decoding with MUSIC. This work appears in [14].

6.5 On the Impact of MIMO Diversity on Higher Layer Performance

We shed light on the cross-layer interactions between the PHY, link and routing layers in networks with MIMO links operating in the diversity mode. Many previous studies assume an overly simplistic PHY layer model that does not sufficiently capture these interactions. We show that the use of simplistic models can in fact lead to misleading conclusions with regards to the higher layer performance with MIMO diversity. Towards understanding the impact of various PHY layer features on MIMO diversity, we begin with a simple but widely used model and progressively incorporate these features to create new models. We examine the goodness of these models by comparing the simulated performance results with each, with measurements on an indoor 802.11n testbed. Our work reveals several interesting cross-layer dependencies that affect the gains due to MIMO diversity. In particular, we observe that relative to SISO links: (a) PHY layer gains due to MIMO diversity do not always carry over to the higher layers, (b) the use of other PHY layer -features such as FEC codes significantly influence the gains due to MIMO diversity, and (c) the choice of the routing metric can impact the gains possible with MIMO. This work appears in [11] and [15].

6.6 Auto-configuring MIMO based 802.11n WLANs

Channel Bonding (CB) combines two adjacent frequency bands to form a new, wider band to facilitate high data rate transmissions in MIMO-based 802.11n networks. However, the use of a wider band with CB can exacerbate interference effects. Furthermore, surprisingly CB does not always provide benefits in interference-free settings, and can even degrade performance in some cases. We conduct an in depth, experimental study to understand the implications of CB. Based on this study we design an auto-configuration framework ACORN, for enterprise 802.11n WLANs. ACORN integrates the functions of user association and channel allocation, since our study reveals that they are tightly coupled when CB is used. We show that the channel allocation problem with the constraints of CB, is NP-complete. Thus, ACORN incorporates an algorithm that provides a worst case approximation ratio of O(1/n). We implement ACORN on our 802.11n testbed. Our experiments show that ACORN (i) outperforms previous approaches that are agnostic to CB constraints; it provides per-AP throughput gains from 1.5x to 6x and (ii) in practice, its channel allocation module achieves an approximation ratio much better than O(1/n). This work appears in [16].

7 Opportunistic Multi-hop Routing, Adaptation, and Congestion

PI: Tara Javidi, Larry Milstein, Rene Cruz
Students: Somsak Kittipiyakul, Qi Que, Andrew Ling, Seok-Ho Chang

7.1 Opportunistic Multi-hop Routing, Adaptation, and Congestion

As a part of the MURI project, PIs Javidi, Milstein and Cruz have used sophisticated methods from stochastic optimization and approximation to investigate and propose optimal cross layer (PHY, MAC, and Routing) and distributed mechanisms for MIMO ad hoc networks [12], [13], [14]. The outcome of these analytic studies resulted in the design of a family of scalable schedulers which, asymptotically, use minimum total power to transfer the information bits for all the end-to-end connections at the requested rates. To this end, we decomposed the multi-hop MIMO network into multiple "decoupled" MIMO broadcast subsystems. In each time slot, each subsystem independently decides the transmit power, the antenna weights, the transmission rates and the forwarding rules of information bits based on the channel state information and previous decisions of other neighboring subsystems. Given a decomposition of the network into MIMO "decoupled" sub-blocks, the proposed algorithms are shown to converge asymptotically to the optimal solution. Even though asymptotic in nature, these algorithms have significant implications for the design of MIMO networks as they 1) established a promising benchmark, predicting significant improvements for many network scenarios, and 2) provide insight in the design of cross-layer optimal resource allocation at the MIMO-MAC and routing layers.

Lott and Teneketzis [8]-[9] were among the first researchers who introduced opportunism in the context of wireless multi-hop routing. Independently, Larssen proposed a fully implemented protocol suite for Selection Diversity Forwarding (SDF) in [10]. In both of these papers, the source identifies a set of potential forwarders and multicasts the message to them. The successful recipients respond with ACKs in the order in which they were listed in the original message header, so that a collision between ACKs is avoided. The source identifies the best amongst these receivers, according to some predefined criteria, and sends a forwarding order to it. Hence, the actual routing decision is made after transmission of data. While [1] suggests time-invariant critera such as hop-count, transmission rate, and transmission energy for making the final forwarding decision, [10] suggests various time-varying criteria, like forward progress, cost progress, queue backlogs etc, for making the final forwarding decision. Extremely Opportunistic Routing (ExOR) [11] is based on the same idea, with differences in the selection metrics.

With a slight twist, [19] considers the issue of diversity routing from the perspective of traffic stability, i.e., guaranteeing a certain vector of flow rates between given source-destination pairs. We would also like to point out that our work in [14] philosophically coincides with formulation in [19], with the main point of difference in our approaches and methodologies: Our work [14] relies on constrained convex optimization and stochastic approximation frameworks to minimize (asymptotically) the expected sum power subject to a constraints on the minimum long-term average rate at theflow level, while [19] uses a Lyapunov -type penalty function as the cost of violating the QoS requirements to establish stability. The Lyapunov drift analysis is, then,

applied to prove the stability, while working within a stochastic approximation framework, our formulation allows for a more general optimization setting. The price of this more powerful methodology is the asymptotic nature of the result. However our more recent work [20] uses the insight obtained from [14] to combine the benefits of [8] and [19] vis-à-vis a congestion diversity measure. Such successful merging of cross-layer diversity routing schemes underlines the significance and promise of the work.

The decision per hop approach raises a number of protocol issues [20]-[21]:
Queueing Delay and Protocol Dynamics: In order to make a local decision on the best next hop node, the queue backlogs as well as channel quality at the receiving nodes needs to be fed back to the transmitting node. In other words, the next "best" hop a dynamically changing option, not only based on channel characteristics and variations but also based on traffic matrix. This can potentially cause oscillatory behavior, whose long-term impacts might be negligible but cause undesirable short term behavior. In other words, while these oscillatory effects tend to smooth out for long flows, they significantly disturb the behavior of short flows.

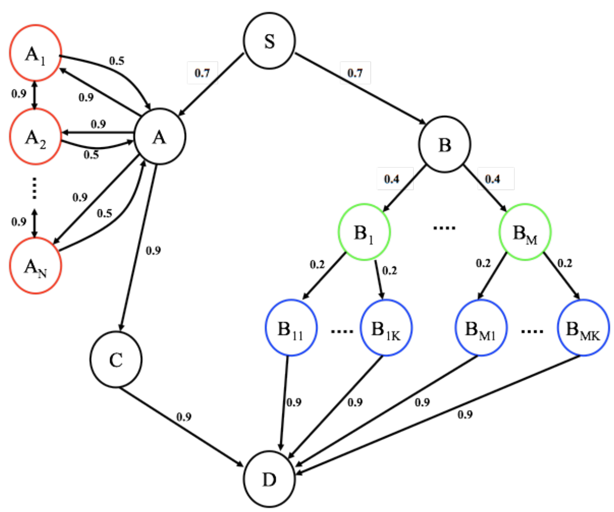

Fig. 1. A multi-hop wireless network

Congestion Problems and Delay-Throughput Trade-off: In many cases, there is an inherent trade-off between packets finding the "shortest" route to the destination and the least congested one. We have been able to show examples, where choosing "shortest" routes can substantially decrease the delay [15]. We have shown that including queuing delay as well as channel quality (both instantaneous state as well as Baysian models) in determining the "distance" to a node is necessary to guarantee an overall desirable behavior. In this, our primary results [15] combine results on backpressure routing [17]-[19] with appropriate concepts from opportunistic routing to improve the delay performance in SISO networks. Our work attempts at taking advantage of diversity in congestion levels across the network without creating unnecessary balancing.

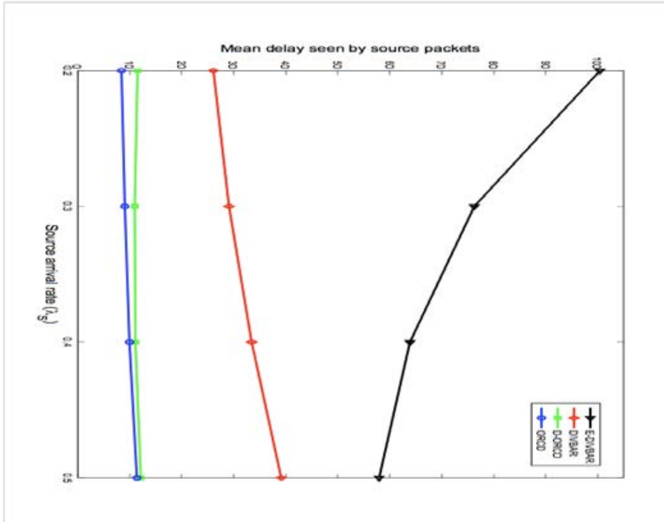

Fig. 2. Delay versus traffic rate (intensity) in the example given in Fig. 1.

Channel Quality Indicator (CQI) and MIMO scheduling: Our work in cross-layer MIMO networking relies heavily on the notion of channel quality to coordinate MAC and routing layer functionalities. In particular, we have relied heavily on the simplicity of our MIMO-BC sub-blocks to identify and adapt instantaneous rate and power schedules. The choice of sub-gradient in this setting was key to obtaining the result.

Channel Quality Distribution (CQD): In order to make a local decision on the best next hop node, the channel quality information is needed. This potentially includes short term indicator (CQI) as well as the channel radio characteristics. While the opportunism reduces the impact of channel estimation error in CQI, the performance of opportunistic algorithms shows a large degree of sensitivity to CQD [7]. An important extension, our work [22] addresses the question of how to account for temporal variation in channel quality as well as effective schemes to construct useful probabilistic models to capture the impact of diversity. In other words, given the stationarity of CQI, one can devise many algorithms to account for receiver diversity in the long term.

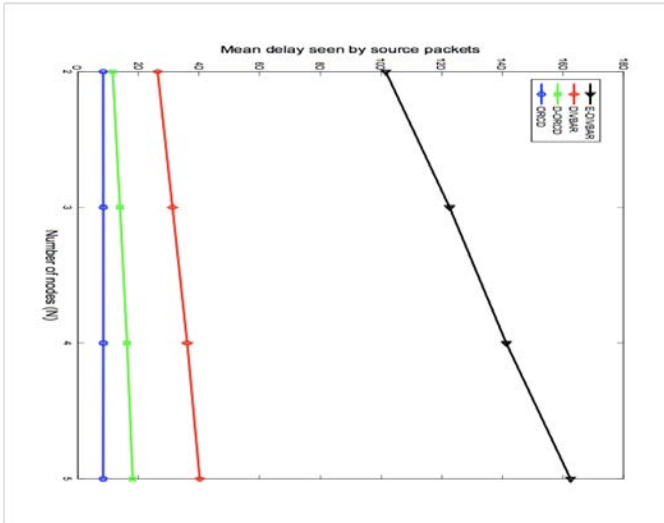

Fig. 3. Delay versus the size of the “hole” A-A , hence, network size.

7.2 High-SNR Cross-Layer Optimization for Delay-Limited Data Transmission in Outage-Limited Wireless Systems

In our previous work [7], we studied the optimal operating point in point-to-point (quasi-static) MIMO channel and the asymptotic expression of the total probability of bit error, where errors occur either due to delay or due to erroneous decoding. The problem setting focused on the case where there is no channel state information at the transmitter (no CSIT) and no feedback, and on the static case of fixed operating parameters. In our recent work [2], we generalize this study to include other outage-limited communication settings, such as cooperative relay [4,5] and fast-fading channels [3]. In these settings, we are interested in the asymptotic high-SNR error performance when the delay bound requirement, D, is finite and small. Given that the asymptotic expression of the total probability of bit error is valid without requiring asymptotically large D, it is then meaningful to ask about the optimal coding block duration, a question which is not answered in our previous studies with asymptotic D. To have a valid expression of the delay violation probability at finite and small D, we assume a class of smoothly scaling (with SNR) bit-arrival processes. This class of processes cover many interesting processes used for traffic modeling.

Our analysis provides closed-form expressions for the error performance, as a function of the channel and source statistics. These expressions identify the scaling regime of the source and channel statistics in which either delay or decoding errors are the dominant cause of errors, and the scaling regime in which a prudent choice of the coding duration and rate manages to balance and minimize these errors. That is, in this latter regime, such optimal choice manages to balance the effect of channel atypicality and burstiness atypicality. We apply the results in the different communication settings discussed above.

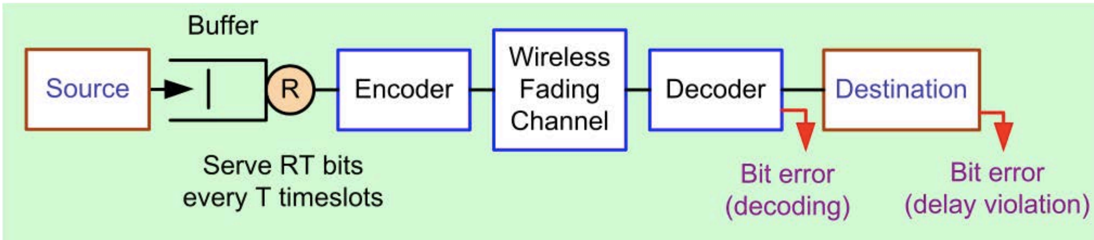

Fig. 4. System model

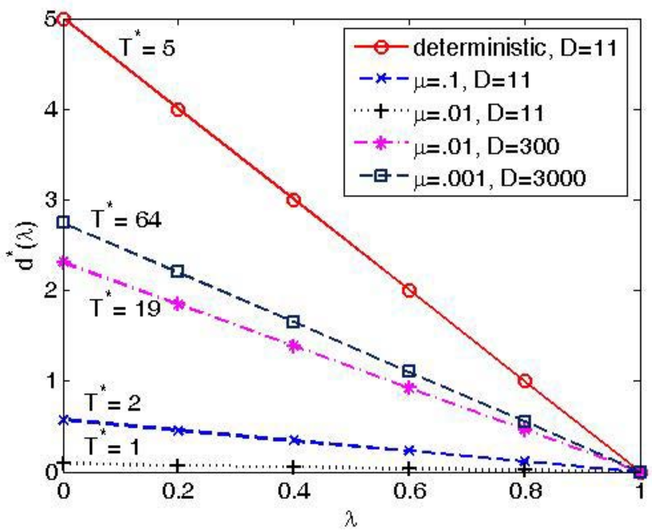

Fig. 5. Exponent of the total error probability for SISO fast fading channel and compound Poisson bit-arrival process

7.3 Many-Sources Large Deviations for Max-Weight Scheduling

This work is an extension of our previous study for MIMO multiple access channel [6] and our recent work described earlier. In [6], we studied the joint optimization of the MAC layer and the physical layer. We formulated and analytically derived bounds on the optimal operating point and the asymptotic (high-SNR and large delay bound D) error performance of MIMO-MAC channel for bursty sources with delay constraints. The adopted system model brings together the four types of gains: diversity, spatial multiplexing, space-division multiple-access, and statistical-multiplexing gains.

To extend the work in [6] to the case when the delay bound D is not asymptotically large, in [1] we look at the queuing performance of the dynamic queue-based (Max-Weight) scheduling policy of a single fixed-capacity server, when the arrival processes are an aggregation of multiple i.i.d. flows. We study a particular scaling of the traffic, known as many-sources scaling, where the number of flows scales with the channel capacity. The interested queuing performance is the asymptotic buffer overflow probability. Assuming a many-sources sample path large-deviation principle (LDP) for the arrival processes, we establish an LDP for the queue length process by employing Garcia's extended contraction principle that is applicable to quasi-continuous

mappings. In the future, we hope to use this result [1] and the result in [2] to extend the work in [6] to multiple access channels.

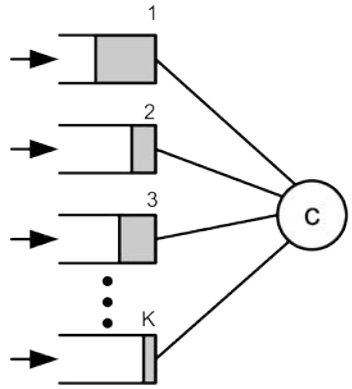

Fig. 6. Multiple-queue, single-server model

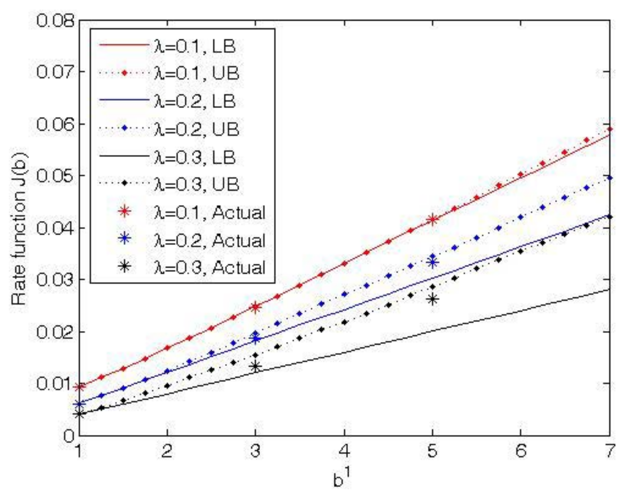

Fig. 7. Example of the actual and the lower and upper bounds of the exponents of the buffer overflow probability where the threshold is (b^1, b^2=1), for compound Poisson bit-arrival process (at various arrival rates) and for two users.

8 Fundamental Limits and Modeling of Approaches for Many to Many Communications in MANETS

PI: J.J. Luna Garcia Aceves

Professor Luna Garcia Aceves has contributed new results for the characterization of many-to-many communication in MANETs. The findings in this project cover two areas:

• The study of fundamental limits for the dissemination of information over MANETs

when many-to-many communication is allowed.
• The modeling of approaches that enable many-to-many communication in MANETs by exploiting processing and storage complexity in mobile nodes.

8.1 Fundamental Limits of Wireless Networks

We completed our work on the characterization of the optimal interference-free capacity of a wireless network subject to unicast traffic, and showing how this order capacity can be attained in the presence of interference by means of [1]. The importance of this work is that no prior work had focused on first establishing what is the optimal capacity of a wireless network in the absence of MAI, and then determining whether that capacity is attainable when MAI is present. In stark contrast to the existing literature, our analysis presents the possibility of actually increasing the capacity of ad-hoc networks with the number of nodes, even while the communication range tends to zero.

We modeled a random network with n nodes, a homogeneous communication range of r(n), and unicast traffic for k source-destination (S-D) pairs. In the absence of interference, such a network corresponds to a random geometric graph (RGG) with an edge between any two nodes separated by a distance less than r(n). We defined a combinatorial interference model based on RGGs, and use it to express all the protocol models used in the past and a model that we later use to show that the optimal capacity of a wireless network is indeed attainable. We generalized prior results by Gupta and Kumar and our own results for wireless networks with MPR, and showed that the optimal capacity of wireless networks is attainable in the presence of MAI. We showed that MPTR achieves the optimal capacity of $\Theta(n^2 r^3(n)/k)$. This constitutes a gain of $\Theta(nr^2(n))$ over any previously reported feasible order capacity.

We also completed our work on the order capacity of wireless networks using network coding (NC). We had previously shown that NC used with MPT and MPR renders the same order capacity as simply using MPT and MPR. Our new results [2, 3, 4] show that NC provides no order gain for multicasting and broadcasting compared to what can be attained with traditional multicasting and broadcasting based on store-and-forward routing. Widely cited experiments [5, 6] have been reported recently in which NC has been used successfully in combination with other mechanisms to attain large throughput gains compared to approaches based on conventional protocol stacks. These empirical results have led many to believe that the combination of NC with wireless broadcasting can lead to significant improvements in the multicast order throughput of wireless networks. However, the exact characterization of the multicast order capacity of NC in wireless networks has remained an open problem since its introduction ten years ago, with only limited results having been reported to date on the subject. We undertook the characterization of the multicast and broadcast throughput order of wireless ad-hoc networks in presence of network coding. We considered a network consisting of n nodes distributed randomly in the network space, with each node acting as a multicast source of a group of m randomly chosen nodes in the network. We have shown that, under the protocol model, the per-session multicast capacity of random wireless ad hoc network in the presence of arbitrary NC has a tight bound of $\Theta(1/\sqrt{mn\log(n)})$ when $m = O(n/\log(n))$ and $\Theta(1/n)$ when $m = \Omega(n/\log(n))$. In addition, we showed that, under the physical model, the per-session multicast capacity of random wireless ad hoc network with arbitrary NC has a tight bound of $\Theta(1/\sqrt{mn})$

when m = O (n /log(n)^3), and $\Theta(1/n)$ when m = Ω(n/log(n)). It has already been established in the literature that the above bounds are achievable on the basis of traditional store-and-forward routing methods. Hence, our results demonstrate conclusively that the throughout gain due to NC for mutlicasting and broadcasting is bounded by a constant factor!

Despite our negative result on the multicast order throughput for NC, the constant-factor gains that can be attained in some cases with NC over store-and-forward routing should not be ignored, and they may be of importance in practical settings. However, our work has also shown that embracing concurrency at the physical layer by means of MPR and MPT provides the same multicast order throughput with or without NC, and that MPR and MPT can be used to attain the optimal unicast capacity in wireless networks [1]. Hence, the effectiveness of using a scheme based on NC to attain higher multicast throughput should be compared against approaches based solely on physical-layer concurrency. In addition, the signaling overhead incurred by the different approaches should be evaluated carefully. Instantiating the necessary NC state at relaying nodes may incur signaling overhead that outweighs any potential throughput gains that NC is intended to provide in the forwarding of data packets.

The last part of our research on the capacity of wireless networks consisted on focusing on techniques that can attain the benefits of distributed MIMO systems with limited cost. We developed and studied [7] an interference management technique for the downlink of a wireless cellular network with which D ($D \leq K$) independent data streams can be broadcasted to D out of M mobile stations with single antenna such that these data streams do not interfere with each other. We demonstrated that D can be any number up to the maximum value of K, as long as M is large enough. Therefore, interference management is capable of achieving the maximum multiplexing gain, as long as there is a minimum number of mobile stations in the network. Surprisingly, by taking advantage of fading channels in multiuser environments, the feedback requirement to transmit K independent data streams is proportional to K, and the encoding and decoding scheme is very simple and similar to that of point-to-point communications.

The original multiuser diversity concept was based on searching for the best channels to use, while our new approach shows that searching simultaneously for the best and worse channels can lead to significant capacity gains. This technique can asymptotically achieve the capacity of dirty paper coding (DPC) when $M \to \infty$. In general, we can have D mobile stations implementing our interference management scheme, where D depends on the number of mobile stations in the network. If D < K, then the rest of $K - D$ mobile stations require to perform cooperative decoding in order to transmit K independent data streams. Our proposed multiuser diversity scheme provides a tradeoff between multiuser diversity and cooperation among mobile stations. This proposed distributed MIMO scheme does not require mobile stations to cooperate, as long as there are enough mobile stations in the network. It achieves optimal K maximum multiplexing gain in the downlink of cellular systems as long as $K \ll M$. If there are not enough mobile stations in the network, partial cooperation among them is required to achieve the maximum multiplexing gain.

8.2 Modeling of Approaches for Many-to-Many Communication in MANETs

The vast majority of analytical models for medium access control (MAC) protocols (e.g.,

see [8, 9]) have assumed an ideal physical-layer model, in which nodes within a given transmission range receive packets with probability 1 if there are no other concurrent transmissions, and packet transmissions fail with probability 1 if there are any concurrent transmissions. This, of course, is not realistic in most practical situations, especially in mobile ad hoc networks (MANETs), where a packet can be successfully received when the received power is larger than a given threshold, the received power levels may show significant variations around a mean power, and even in the presence of multiple access interference (MAI) caused by concurrent transmissions, receivers can decode packets with probability less than 1. The decoding probability together with MAC protocol behavior determine the performance of MAC protocols in MANETs.

In reality, the received signal is a combination of many replicas arriving over multiple paths between the transmitter and receiver. The signal on these different paths can interfere with each other constructively or destructively; this multi-path effect causes the received signal and power to become variables of space. Especially, if the transmitter or the receiver moves, channel fading causes the received signal and power to become variables of time as well. In addition to above propagation impairments caused by imperfect channel conditions, noise and MAI caused by other concurrent transmissions also impact the probability of correct packet reception. Many MAC protocols employ carrier sensing to mitigate MAI by listening channel status before packet transmissions. As a result, a node transmission probability depends on the channel conditions and is different in carrier-sensing MAC protocols than in MAC protocols without carrier sensing.

While the importance of the physical-layer effects on the performance of MANETs is well recognized, most prior analytical models of MAC protocols operating in MANETs avoid their characterization for the sake of simplicity. For example, Carvalho et al. [10] use linear approximations for the relationship among probabilities of the channel being busy, a node transmitting, and a packet being received successfully, and do not account explicitly for the effect that network density, node mobility and other physical-layer factors have on the performance of MAC protocols.

A few works have attempted to analyze those realistic physical layer factors and incorporate their effect in the modeling of MAC protocols. Pham et al. [11, 12] have tried to take imperfect channel conditions into consideration; however, they only analyze IEEE 802.11 DCF and assume only one specific channel condition, namely Rayleigh channel fading. In addition, they assume that a transmission fails if more than one packet is transmitted concurrently, while in reality a successful packet reception is determined by the signal to interference plus noise ratio (SINR). Zheng et al. [13] generalized the effect of imperfect channel conditions by making the strong assumption that bits are transmitted with a fixed error probability, which provides a wider application area for the model; however, their assumption is also not practical, because there are many network parameters in MANETs that can impact the packet reception probability, such as traffic rate, network density, and mobility.

We have worked on developing a model that takes into account imperfect channel conditions and multiple access interference, and proposed a generalized, parameterized framework for representing the interaction between the physical (PHY) and MAC layers. The focus in this work is not in providing an exact representation of specific MAC protocols. Rather, we aim to model

generic MAC protocols in which either an efficient interference prevention scheme is employed or not, and extract common properties of those protocols. We have used two well known examples of those two types of MAC protocols, namely IEEE 802.11 DCF and Aloha, and verify the correctness of our models via simulations. Our first results have been submitted for publication, and our plan is to apply the model to the study of different MIMO schemes. We aim at the analysis via simulation and our analytical framework of specific protocols based on MIMO techniques. More specifically, we are studying the behavior of AMPTR (adaptive multi-packet transmission and reception), which is a MAC protocol aimed at exploiting MPR and MPT.

9 Conclusions

Significant advances in MIMO ad hoc network have been made in virtually all the components of a tactical ad hoc network over the course of this project. We have expanded the understanding of the underlying principles for the design of MIMO antennas, developed MIMO channel models based on experimental data, developed a range of approaches to implement MIMO transmitters and receivers with limited feedback requirements, developed improved STC and beamforming techniques, and developed MAC scheduling and routing protocols with neighbor discovery and tracking based on MIMO spatial information. We have made extensive advances in understanding how to best utilize the diversity afforded by the MIMO nodes in realistic channels.

One of the main conclusions that can be drawn from this work is that equipping the nodes of a tactical network with MIMO transmitters and receivers provides the ability to greatly improve network capacity, robustness and quality of service. One of the most significant reasons for these gains comes from the ability to provide multiple simultaneous data streams that can be utilized for multi-packet reception at the nodes of the network. Further enhancements depend on understanding how to manage the power allocated between the various streams to manage the interference generated for nearby nodes in a time-varying tactical channel. A major issue in optimizing the MIMO ad hoc network performance in a time varying channel is that many of the important parameters are time varying and must be estimated from the current data. In addition the time scale for the variations in physical layer parameters is rapid compared to the time scales needed for developing reliable routing protocols.

Additional work is required to optimize the methods by which the physical layer is incorporated into the routing and scheduling protocols in a mobile, tactical ad hoc network, but our results have shown that there is great promise in employing MIMO nodes in ad hoc networks. MIMO nodes have been shown to provide a number of approaches to efficiently disseminate the information through the network that can be exploited to improve network performance.

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2.0 Physical Layer Considerations for MIMO Ad Hoc Networks
2.1 Antenna Design for Diversity and MIMO Systems
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